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This report presents procedures for the engineering design and control of pulp and paper-mill sludge disposal landfills. Engineering design will allow more efficient use, thereby contributing to economic and environmental benefits. To form the basis for engineering design of sludge material, the methodologies and theories of soil mechanics were applied. The methodologies should be applicable to most compositions of sludge materials. Some sludge materials may have peculiarities associated with testing, field workability, and behavior. However, from accumulated experiences of applying the procedures of this manual, the manual can be adjusted and expanded.

This report is specifically written for pulp and paper-mill personnel of technical background but with little or no exposure to the soil mechanics discipline. The procedures are such that these individuals can rationally approach a landfill operation to attain efficiency and optimization. This report does not present a rigorous treatment or analysis of sludge material, but it does give the above-mentioned individuals the procedures for determining good approximations of sludge behavior. Individuals interested in more rigorous and theoretical analysis of sludge behavior should consult the list of references.

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DESIGN CONSIDERATIONS FOR PULP AND PAPER-MILL SLUDGE LANDFILLS

by

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Interagency Agreement No. EPA-IAG-D5-F657

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FOREWORD

The Environmental Protection Agency (EPA) was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollution discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communication's link between the researcher and the user community.

This report is a result of research supported by the EPA to obtain engineering information essential to the design of environmentally acceptable paper-mill sludge landfills.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This report presents useful considerations for the engineering design and control of pulp and paper-mill sludge disposal landfills. Engineering design will allow more efficient use, thereby contributing to economic and environmental benefits. To form the basis for engineering design of sludge material, the methodologies and theories of soil mechanics were applied. The methodologies should be applicable to most compositions of sludge materials. Some sludge materials may have peculiarities associated with testing, field workability, and behavior. However, from accumulated experiences of applying the procedures of this manual, the manual can be adjusted and expanded.

This report is specifically written for pulp and paper-mill personnel of technical background, but with little or no exposure to the soil mechanics discipline. The procedures are such that these individuals can rationally approach a landfill operation to attain efficiency and optimization. This report does not present a rigorous treatment or analysis of sludge material, but it does give the above-mentioned individuals the procedures for determining good approximations of sludge behavior. Individuals interested in more rigorous and theoretical analysis of sludge behavior should consult the list of references.

This report is submitted in fulfillment of Interagency Agreement No. EPA-IAG-D5-F657 between the U. S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Solid and Hazardous Waste Research Division (EPA, MERL, SHWRD), and the U. S. Army Engineer Waterways Experiment Station (WES). Work for this report was conducted during the period January 1975 to January 1976.

This project was conducted by personnel of the Soils and Pavements Laboratory (S&PL), WES, under the general supervision of Mr. James P. Sale, Chief of S&PL. Mr. Richard H. Ledbetter prepared this report.

Directors of WES during the preparation and publication of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

	Page
Foreword	iii
Abstract	iv
List of Figures and Plates	vi
List of Tables	viii
List of Abbreviations and Symbols	ix
Acknowledgements	xiv
I The Nature and Disposal of Paper Industry Primary Sludges	1
II Retaining Structures	13
III Consolidation, Settlement, and Slope Stability	19
IV Field Experimental Example	27
V References	38
Figures 1-24	
Tables 1-8	
Plate 1	
A Metric Conversion Table	71
B Testing Procedures for Sludge Properties	72
Figures B-1 through B-18	
Tables B-1 and B-2	
Plates B-1 through B-13	

LIST OF FIGURES AND PLATES

Number		Page
1	Variability of sludge properties	41
2	Relationship of sludge dewaterability to ash content	42
3	Solids content versus ash content	43
4	Mass of leachate constituents	44
5	Dike and sludge cross section	45
6	Plan for landfill	46
7	Sludge landfill construction steps	47
8	Weight and volume relationships	48
9	Compressed sample	49
10	Load-depth diagram	50
11	Load increment added to a sludge layer	51
12	Time factors for consolidation analysis	52
13	Nomograph for consolidation with vertical drainage	53
14	Time factors for consolidation analysis with gradual load application	54
15	Slope analysis	55
16	Correction factor for converting vane shear strengths to field shear strengths	56
17	Experimental landfill, plan view	57
18	Typical cross section of experimental landfill	58
19	Consolidation characteristics of sample sludge	59
20	Comparison of predicted and measured time-settlement curves, lower sludge layer	60
21	Comparison of actual and predicted time-settlement curves, upper sludge layer	61
22	Experimental landfill vane shear strength immediately before slope excavation	62
23	Cut slope in experimental sludge landfill	63
24	Cross section of top sludge layer for stability analysis	64
B-1	Determining the weight of a sludge specimen submerged in water	109

Number		Page
B-2	Evacuating air from samples in determination of specific gravity	109
B-3	Typical calibration curve of volumetric flask	110
B-4	Stages of consistency	110
B-5	Liquid limit device	111
B-6	Details of liquid limit device	112
B-7	Grooving liquid limit specimen	113
B-8	Closed liquid limit groove	113
B-9	Plastic limit determination	113
B-10	Crumbling of threads at plastic limit	113
B-11	Apparatus for determining the volume of dry sludge pat of shrinkage limit test	114
B-12	Typical consolidometer (fixed-ring type) with falling-head device for permeability test	115
B-13	Typical retainer ring	116
B-14	Time-consolidation curve	117
B-15	Square root of time-consolidation curve	118
B-16	Determination of height of capillary rise	119
B-17	Void ratio-pressure curve	120
B-18	Vane shear test equipment	121
1	Settlement-Time Plot	70
B-1	Water Content - General	124
B-2	Unit Weights (Volumetric Method)	125
B-3	Unit Weights (Displacement Method)	126
B-4	Specific Gravity Tests	127
B-5	Liquid and Plastic Limit Tests	128
B-6	Shrinkage Limit Test	129
B-7	Consolidation Test (Specimen Data)	130
B-8	Falling-Head Permeability Test with Consolidometer	131
B-9	Consolidation Test (Time-Consolidation Data)	132
B-10	Consolidation Test - Time Curves	133
B-11	Dial Reading Versus Time-Data for Each Load Increment	134
B-12	Consolidation Test (Computation of Void Ratios)	135
B-13	Consolidation Test Report	136

LIST OF TABLES

Number — Page

1 Primary Sludge Production Associated with Paper Manufacturing 65

2 "Normal" Sludge Composition 65

3 Physical Characteristics of Sludges Originating in High Ash Sludge Landfills 66

4 Fibre Classification for Selected High Ash Sludges 66

5 Analysis of Leachate Quality 67

6 Trace Elements Contained in Paper-Mill Primary Sludge 68

7 Leachate Attenuation Properties of Soils 68

8 Physical Properties of Paper-Mill Sludge 69

B-1 Relative Density of Water and Correction Factor K for Various Temperatures 122

B-2 Correction Factor R_T for Viscosity of Water at Various Temperatures 123

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

BOD -- biochemical oxygen demand
°C -- degrees Centigrade
cm -- centimetres
cm^3 -- cubic centimetres
COD -- chemical oxygen demand
deg -- degrees
EPA -- Environmental Protection Agency
ft -- feet
in. -- inches
in.^{2}/min -- square inches per minute
kg/cm^2 -- kilograms per square centimetre
lb/ft^2 -- pounds per square foot
lb/ft^3 -- pounds per cubic foot
lb/ton -- pounds per ton
LL -- liquid limit
mg -- milligrams
mg/ℓ -- milligrams per litre
mm -- millimetres
MTU -- turbidity
pcf -- pounds per cubic foot
PI -- plasticity index
PL -- plastic limit
psf -- pounds per square foot
sec^2/g -- seconds squared per gram
SL -- shrinkage limit
T/ft^2 -- tons per square foot
T/m^2 -- tons per square metre
μmho/cm -- micromhos per centimetre

SYMBOLS

A -- cross-sectional area

A_c -- ash content

a -- area

C -- volumetric change from a given water content w (usually the liquid limit)

$CaCo_3$ -- calcium carbonate

Cd -- cadmium

Cr -- chromium

Cu -- copper

C_a -- coefficient of secondary compression

C_c -- compression index

C_v -- coefficient of consolidation

D -- diameter

D_o -- initial dial reading

e -- void ratio

e_f -- void ratio after test

e_o -- initial void ratio existing at P'_o

F -- safety factor

Fe -- iron

G_s -- specific gravity of solids

H -- height

H -- length of longest vertical path for drainage of water

Hg -- mercury

H_f -- height of specimen at end of test = $H - \Delta H$, in., where ΔH is the net change in height of specimen

H_i -- average height of the specimen for the load increment

H_s -- height of solids

H_t -- total thickness of sludge layer

H_v -- height of voids

H_{wf} -- final height of water

H_{wo} -- original height of water

h -- height

h_c -- height of capillary rise

h_t -- height of tailwater

h_1 -- initial height of water in standpipe
h_2 -- final height of water in standpipe
i -- hydraulic gradient
K -- correction factor based on density of water at 20°C
k -- coefficient of permeability
k_{20} -- coefficient of permeability at 20°C
L -- height
L_s -- linear shrinkage
Mg -- magnesium
n -- individual layers of different sludge within a single layer of sludge
Ni -- nickel
O_c -- organic content
P -- load pressure or stress
Pb -- lead
P' -- effective pressure or stress
P'_{lower} -- effective pressure or stress, lower layer
P'_{upper} -- effective pressure or stress, upper layer
P'_o -- average initial effective stress within sludge layer
P_o -- total initial stress
p -- load pressure
q -- rate of fluid discharge
R -- shrinkage ratio
R_T -- correction factor for viscosity of water at 20°C
S -- degree of saturation
S_o -- initial degree of saturation
S_U -- undrained shear strength
s -- solids content
T -- dimensionless time factor
T_{max} -- maximum torque
t -- time
t_f -- final time
t_o -- end of construction time
t_{pri} -- time for primary consolidation
t_{sec} -- time for secondary consolidation

t_{total} -- time for total settlement
U -- percent of primary consolidation
u -- pore hydrostatic pressure
V -- volume
V_f -- volume of landfill
V_s -- volume of solids
W -- total weight
W_s -- weight of dry solids
W_w -- weight of water
W_{bw} -- weight of flask plus water
W_{wf} -- weight of water in specimen after test
W_{wo} -- original height of water
W_{bws} -- weight of flask plus water plus solids
w -- water content
Zn -- zinc
z -- depth
α -- angle
β -- slope angle
γ_d -- dry unit weight
γ_m -- wet unit weight
γ_w -- unit weight of water
ΔD -- change in height of specimen
ΔH -- change in height
ΔH_s -- decrease in specimen height over log cycle
ΔH_{pri} -- primary settlement
ΔH_{sec} -- secondary settlement
ΔH_{total} -- total settlement
$\Delta H_{pri_{lower}}$ -- primary settlement, lower layer
$\Delta H_{pri_{upper}}$ -- primary settlement, upper layer
$\Delta H_{sec_{lower}}$ -- secondary settlement, lower layer
$\Delta H_{sec_{upper}}$ -- secondary settlement, upper layer
$\Delta H_{total_{lower}}$ -- total settlement, lower layer

$\Delta H_{total_{upper}}$ -- total settlement, upper layer
Δh -- corrected tailwater = $h_t + h_c$
ΔP -- total load above sludge layer
ΔP_{lower} -- total load acting on the lower sludge layer
ΔP_{upper} -- total load acting on the upper sludge layer
$\Delta X, \Delta x$ -- slice width
ΔV -- change in volume
ϕ -- angle of internal friction

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Mr. Duane W. Marshall of the National Council of the Paper Industry for Air and Stream Improvements, Inc., wrote Section I of this report. Field and laboratory investigations of sludge material were conducted by Dr. O. B. Andersland during the period 1970-1974.

SECTION I

THE NATURE AND DISPOSAL OF PAPER INDUSTRY PRIMARY SLUDGES

INTRODUCTION

Associated with the application of conventional and advanced wastewater treatment technologies, but often obscured by the benefits to receiving-stream quality, is the accumulation of waste constitutents into either a highly concentrated solution or aqueous suspension of residual solids commonly described as sludge. Where those concentrated residuals have no potential for reuse or by-product development, they must be further processed for ultimate disposal to the environment. In doing so, the land as a practical matter represents the ultimate repository in all but those instances where (a) the incineration of organic components and subsequent discharge of combustion products to the atmosphere constitutes a viable alternative or (b) the limited opportunity of ocean disposal exists.

For many years, the disposal of wastewater treatment sludges has been regarded as a problem as great or greater than that of treating the waste itself (1). Furthermore, the generation of large quantities of hydrous residues associated with the increasing degrees of waste treatment mandated by existing regulation has perpetuated, if not amplified, the problem. Though the dewatering and disposal of these residual solids are widely recognized to represent a significant fraction of the costs for wastewater treatment, Dick (2) justifiably concludes that "the attention which has been given to sludge treatment and disposal in the past, as compared to processes for initial removal of pollutants, has been more nearly proportional to the relative volume of sludge than to the relative cost of sludge disposal." Moreover, if overall control strategies are to result in minimal net environmental impact, issues relevant to the accumulation and subsequent management of those residual solids must be thoroughly weighed in the development of comprehensive environmental regulation sensitive to intermedia effects. Included among those issues are the protection and/or optimum utilization of land resources.

Among the solids that are accumulated in the treatment of wastewaters of pulp and paper origin are those lost from the papermaking process and subsequently separated during primary clarification. These solids are composed of fibre, filler, and coating clays, and in the case of those manufacturing categories in which wastepaper constitutes a significant portion of the product furnish, considerable quantities of impurities. Information compiled by Miner (3) and shown in Table 1 indicates that solids losses from most categories of paper manufacture represent from 2 to 4 percent of production. Exceptions include waste-paperboard where the nature of the paper grade produced at nearly half of the installations surveyed permitted return of primary sludge to the production process. The relatively large losses from deinking operations are associated with removal of inks and other nonfibrous materials from a wastepaper furnish. Recently reported results (4) of a survey of pulp and paper mills indicated that 78 percent of the sludge generated at those mills responding to the survey was disposed of either in or on the land. Thus, land disposal remains the largest single method of sludge management practiced in the pulp and paper industry.

Emerging land-use patterns and the decreasing availability of land considered acceptable for landfill pose a potential constraint to continued land disposal practice in many areas. In those cases where the fibre or organic content of the primary sludge is at least 50 percent, incineration presents a feasible alternative. In fact, 15 percent of the sludge generated at mills responding in the above-cited survey was disposed of by incineration. However, costs associated with separate incineration of sludges in quantities commonly found at mills have largely limited the practice to those integrated operations with wood fuel boilers.

In addition, the composition of sludges generated at many installations further restricts the practice of incineration. Data reported by Gillespie et al. (5) and shown in Table 2 indicate that sludges with ash contents exceeding 50 percent are commonly associated principally with the manufacture of (a) board, (b) deinked pulp and paper, and (c) integrated and nonintegrated fine papers. Furthermore, the economic impetus for greater fibre recovery and utilization will likely result in sludges of progressively greater inorganic content. Incineration is not a realistic alternative for those sludges because of (a) their relatively low organic content, (b) the attendant low moisture requirements necessary for self-supporting combustion, and (c) the inevitable necessity for further land disposal of the predominant inorganic fraction. Barring by-product recovery opportunities, land disposal remains the only feasible alternative in that situation.

Of the mills which must deal with the disposal of high ash sludges, more than 100 are located in or adjacent to metropolitan areas where land available for solid waste disposal is limited. As a consequence, it will be incumbent upon those mills, and probably others as well, to optimize landfill disposal by the application of sound engineering principles to all stages of site selection, design, operation, and ultimate land use. Factors warranting consideration in such an approach would include the significance of sludge composition to its engineering behavior, as well as the environmental implication involved.

The variability of sludge composition from site to site and the complex interaction of those sludge constituents known to influence landfill behavior require the assessment of a sludge's engineering characteristics by means of functional tests known to be of significance to the rational design of a landfill to attain some given objective, inclusive of a given rate or degree of consolidation, associated rate of leachate discharge, or ultimate land use. It was in this context that the National Council of the Paper Industry for Air and Stream Improvement sponsored initial efforts by Andersland (6,7) aimed at documenting the applicability of traditional soil mechanics techniques for relating basic engineering properties of dewatered sludges, specifically shear strength, permeability, and consolidation. The utility of those tests for prediction of actual landfill behavior has been verified for one composition of sludge in subsequent work conducted by Andersland and sponsored by the Environmental Protection Agency (EPA) Division of Solid Waste Research (8,9). In illustrating the principles and knowledge previously gained, the remaining sections of this manual are advanced in the following context:

a. This report identifies useful consideration in the engineering design and control of pulp and paper-mill sludge disposal landfills. Engineering design will allow more efficient use, thereby contributing to economic and environmental benefits. The pulp and paper industry will benefit economically by being able to dispose of larger quantities of sludge in a given landfill than past practices permitted. Also, after completion of landfills, they could be used for recreational purposes benefitting the public, or as real estate investments benefiting the pulp and paper industry.

b. Andersland's investigations were carried to completion by field experiment for only one composition of sludge material. However, the methodology should be applicable to most other sludge compositions. Sludge material other than that used by Andersland may have peculiarities associated with testing, field workability, and behavior. However, from accumulated experience of applying the tests and procedures of this report, the report can be adjusted and expanded. In addition to landfill design considerations, the test procedures can be used as a measure of the effectiveness of dewatering processes. The example material and procedures of this report are based on Andersland's investigations.

c. This report is written specifically for pulp and paper-mill personnel of technical background, but with little or no exposure to the soil mechanics discipline. The procedures are such that the above mentioned individuals can rationally approach a landfill operation to attain efficiency and optimization. This report does not present a rigorous treatment or analysis of sludge material, but it does give the above-mentioned individuals the procedures for determining good approximations of sludge behavior. Individuals interested in more rigorous and theoretical analysis of sludge behavior should consult the list of references.

SLUDGE COMPOSITION, ITS IMPACT ON ENGINEERING BEHAVIOR

Paper industry primary sludges are commonly characterized by the relative proportion of either the combustible or fixed solids (10) comprising the sludge mass. However, a characteristic of equal prominence from the perspective of solids handling and disposal is the water content, which may represent 90 to 98 percent of the sludge mass, as illustrated in Table 2.

Water Relationships

Gehm (11) has classified the water associated with paper-mill sludges as either free, interstitial, or water of imbibition. The free water is considered readily separable and constitutes but a small fraction of a thickened sludge. Water of imbibition characterizes water chemically bound or physically trapped within the lattice structure of colloidal sols. It cannot be removed by mechanical means and, as such, would pose a limiting condition to the capabilities of such dewatering technology. However, the water of imbibition represented less than 2 percent of the water associated with cellulosic residues evaluated by Zettlemoyer (12) in his study of the surface properties of hydrogels resulting from treatment of pulp and paper-mill effluents. As a consequence, such a small proportion of water of imbibition does not characterize the dewatering properties of paper-mill sludges. Rather, Zettlemoyer concludes that interstitial water held in the pores of the system by surface energy phenomena amounts to greater than 90 percent of the water associated with a thickened sludge.

The rate and extent of interstitial water separation are best defined in terms of the composition and nature of the sludge solids.

Solids Composition

Noncombustible Fraction--

The noncombustible fraction consists primarily of such filler materials as kaolin clays and titanium dioxide, with possible quantities of silicates and carbonates. Their composition and physical properties, as well as other pigments finding specialized application in paper manufacturing, are detailed elsewhere (13). The most striking characteristic of those solids from the perspective of sludge dewatering lies in their fine particle size, predominantly smaller than 2μ.

In addition to variation among various production categories, sludge ash content is observed to have considerable daily variation at individual installations, dependent upon the grade manufactured and performance of fibre recovery systems. The variation over a 40-day period at a mill manufacturing fine papers is shown in Figure 1, along with the corresponding variation in sludge filterability.

Comparison of those variables indicates that the impact of the inert component alone is insufficient to explain the variation in sludge filterability.

Organic Constituents--

The organic fraction may consist of fibre and such colloidal components as highly hydrated wood dust, fibre debris, ray cells, starches, dextrines, resins, and protein. Though but a small proportion of the sludge mass, the colloidal components exert a disproportionate effect upon the filtration properties of paper-mill sludges.

The fibrillar structure of cellulosic components and the associated size of interstices impart a capacity for the retention of water by capillary forces. Fibre length, or otherwise particle size, of cellulosic constituents poses a further determinant of the dewatering characteristics. The separation of water is restricted by the size of passages available for flow which in turn is a function of particle size and particle size distribution. The relative importance of various size fractions has been established in studies of the relationship between the constitution and the dewatering properties of hydrous sludges (14). Fractions smaller than 200 mesh were observed to be capable of much greater compaction with the resulting smaller pore sizes yielding greater resistance to flow and greater retention of water by capillary action. In contrast, the fraction greater than 60 mesh was relatively easily dewatered. Chemical composition is of additional influence due to the potential presence of swellable polysaccharides among the finer size fractions. They represent the principal constituent capable of binding water at the molecular level (water of imbibition). More importantly, however, the deformability and conformability of such particles dictate the degree to which compaction can result in a corresponding sealing of the sludge interstices.

Observed Behavior

The physical characteristics shown in Table 3 were compiled in the course of studying core samples extracted from existing high ash sludge landfills (15). The deposits, ranging in age from 3 months to 20 years, showed considerable vertical stratification reflective of changes in paper grades produced and fibre recovery practices. The presence of long fibre (greater than 100 mesh) in quantities constituting approximately 20 percent of the sludge mass may be considered representative. In most cases, the fraction passing the 200-mesh sieve exceeds the ash content and is indicative of the extent to which troublesome cellulosic fines are present. A more detailed classification of fibrous components greater than 100 mesh for several mills generating high ash sludges is shown in Table 4 (3). The data would suggest that size distribution is specific to individual mills, though the fibre present for the mills shown is predominantly smaller than 38 mesh.

The interacting effects of particle size, composition, and solids consistency on sludge drainage can be best assessed in terms of their influence on sludge porosity. The fine particles common to both the organic and noncombustible fractions exert a dominant physical effect upon sludge dewaterability.

The resistance of sludges to filtration is particularly sensitive to particle size and is substantially increased by the presence of fines. The significant reduction in the proportion of voids inherent with particles of such small size, as well as their lodging within the interstices of larger particles, constitutes an obstacle to the migration of water within the sludge mass. In illustrating their impact, Gale (16) projects that a ten-fold decrease in effective particle size would result in a 100-fold decrease in filterability.

The predominance of fines in high ash sludges has been observed to impart virtual impermeability to dewatered cakes. Studies with pulp suspensions (14) have demonstrated decreasing filterability as a consequence of successive addition of clay. In the course of successfully demonstrating the applicability of geotechnical engineering tests and principles to high ash sludge landfill behavior, Andersland (6) observed that sludge permeability progressively deteriorated as organic content was decreased from 43 to 28 percent by removal of long fibre. However, over that range of organic contents, sludge permeability was also dramatically decreased by increases in cake consistency.

This parallels observations with mechanical sludge dewatering that the beneficial presence of fibre longer than 100 mesh was diminished as slurry consistency was increased for those sludges high in colloidal content. Thus, sludges become increasingly impermeable with progressive dewatering or consolidation. Andersland (7) also observed that higher sludge solids content results in a reduced rate of consolidation, thus requiring greater time to reach ultimate settlement.

Recognizing the importance of sludge cake consistency, the distinction needs to be made between the rate and extent that water can be expressed from sludges. Notwithstanding their lower permeability, high ash sludges also exhibit a reduced capacity for retention of water which is attributable to the denser, nonporous structure of individual clay particles in contrast to properties of organic components likely to be present. Laboratory study (17) documents the likelihood of greater filter cake consistencies being associated with higher ash content sludges. Confirmation is seen in Figure 2 which illustrates an increasing trend of cake consistency with greater ash content observed for numerous installations employing either vacuum filtration or centrifugation for the mechanical dewatering of primary sludges (3). A similar observation was made by Mazzola (15) for sludge samples taken from various in-depth landfills at nine installations, as shown in Figure 3. An associated observation was that sludge moisture contents had changed very little with time.

Another factor of importance to sludge permeability, but not inherent with its composition, is the presence of minute gas bubbles incorporated during dewatering or entrapped during placement of sludge in the landfill. Andersland (6) concluded that undissolved gas in the sludge pore fluid was responsible for reduced permeability, and, as a result, a certain hydraulic gradient was necessary to induce flow at low back pressures. Though the effect of gas bubbles on permeability persisted up to back pressures ranging from 60 to 120 ft (see Appendix A, Metric Conversion Table) of water, the magnitude of the threshold gradient decreased with an increase in back pressure. As an example, it was reported that for a secondary fibre mill sludge and zero back pressure, this gradient was as high as 1177. This is of practical significance to the drainage and subsequent consolidation of sludge since hydraulic gradients in field embankments can be less than one.

Summary

The separation of water from paper industry primary sludges is predominantly a function of those factors which determine the size of interstices available for fluid flow. As a further analogy, Andersland (6) has cited that the permeability of pulp and paper-mill sludges is dependent upon the same variables as those for soils. These reduce to (a) particle size, (b) particle size distribution, and (c) the deformability or conformability of sludge fines as a consequence of chemical composition.

The capacity, then, for sludge solids to dewater or consolidate in landfills will decrease as the relative proportions of ash and organic fines are increased. Permeabilities are further deteriorated with progressive increase in cake consistencies and the presence of entrapped gases within the sludge interstices.

ENVIRONMENTAL CONSIDERATIONS

Implicit with the optimization of landfill disposal sites by the application of sound engineering principles is consideration of the overall impact upon the environment. As a consequence, the potential for intrusion into the groundwater of constituents associated with the sludge and its subsequent decomposition warrants attention. If leachates on a case-by-case basis show a potential, according to the proposed standards of the Federal Water Pollution Act Amendments of 1972, for pollution of receiving waters whether ground or surface, necessary actions should be taken in order to prevent contaminants from reaching the receiving waters. The likehood of groundwater contamination can be compacting the landfill bottom material to a permeability of less than 1.75 x 10^{-3} cm per sec or by using a layer of impervious clay or synthetic material. In addition, leachates will have to be collected.

Leachate Composition

Leachates originating within landfills may be characterized as being high in dissolved solids and chemical oxygen demand (COD) and biochemical oxygen demand (BOD). Data contained in Table 5 illustrate leachate composition observed in studies of an experimental high ash sludge landfill in West Carrollton, Ohio (8).

Leachate constituents present in the greatest quantities are dissolved organic matter, mineral salts, and those contributing to specific conductance, and alkalinity. Alkalinity was consistently greater than total hardness, indicating that hardness was entirely of carbonate origin. Consistent with the buffering capacity associated with leachate alkalinity, pH varied over the narrow range of 7.5 to 7.8. Such a pH is uncharacteristic of domestic landfill leachates whose acidic nature and lower pH values tend to reduce exchange capacities of renovating soils (18). Specific conductance values observed in this study do exceed the single value of 3000 μmho/cm cited by Emrich (19) in illustrating that parameter as an example of persistence for as long as 20 years of pollution potential of leachate emanating from landfills of municipal refuse. Concentrations of BOD, hardness, and dissolved solids, reported for leachates originating from landfills of domestic refuse, span a wide range and encompass the values observed in this study (18, 20, 21, 22). A ratio for BOD to COD of 0.68 was also observed over the duration of the 2-year study. With the exception cited above, suspended solids did not exceed 160 mg/ℓ, nor was turbidity in excess of 56 MTU. Considering the origin of the fill material utilized for this evaluation, it is not surprising that leachates would be nearly void of organic nitrogen and phosphorus. In a number of instances, concentrations of iron and chloride in Samples I through V nominally exceeded the 0.7- and 181-mg/ℓ concentrations for those respective constituents in the in situ sample, suggesting the possibility of some leaching from the drainage beds or, perhaps, a decrease in those residuals by the conclusion of the study. Concentrations of nitrogen and phosphorus, as well as chloride and sulfate, are significantly less than reportedly present in domestic landfill leachates.

Whatever similarities might be suggested between leachate concentrations typical of this study and domestic landfills, the significant differences in the mass of constituents discharged is made apparent in Figure 4. The high-ash-sludge landfill constituent mass was estimated assuming a hypothetical leachate strength as great as that represented by the dry weather concentrations for the entire volume displaced. Representative domestic refuse landfill masses were estimated based upon data reported by Merz (21). Based upon those estimates, the mass of BOD per unit weight of dry solids associated with the high ash sludge was but 7 percent of that reported for domestic refuse; alkalinity approximated 40 percent.

These distinctions between landfills containing paper-mill sludge and municipal refuse are advanced only to illustrate that the arbitrary application of regulations developed for municipal sanitary landfills is not warranted. Rather, implementation of regulation should reflect what is known of sludge composition and associated leachate characteristics.

The presence of heavy metals and other elements considered hazardous to public health is not characteristic of paper-mill sludges. With the possible exception of zinc, those compounds are not inherent in the paper manufacturing process and originate as trace components in raw materials. As a result, they appear in only trace amounts in mill sludges, as shown for several mills in Table 6. The use of zinc compounds as brightening agents for groundwood pulps and clays accounts for its occasional presence in more significant concentrations. However, the increasing substitution of other brightening compounds will progressively diminish the occurrences of zinc in paper-mill sludges.

The alteration of the composition and properties of a fill's organic components by microbial attack could result in the loss to the leachate of intermediate metabolic products. In the case of paper-mill sludge landfills, the anaerobic environment, as well as the absence of such supplemental nutrients as nitrogen and phosphorus, significantly retards the degradation of the fibrous sludge constituents. From a survey of literature data on nitrogen and phosphorous requirements for cellulose degradation, Springer (23) estimated that from 2 to 60 mg of nitrogen and from 1 to 10 mg of phosphorus per gram of cellulose were required for cellulose decomposition. Imshenetsky (24) has reported that decomposition of cellulose becomes essentially inactive when available nitrogen becomes less than 1.2 percent.

Paper products have been found virtually unchanged in landfills that had been completed for 15 to 25 years. Mazzola's observations of high-ash-sludge landfills further substantiate the slow rate of decomposition. On the basis of photomicrographs of core samples, fibre contained in samples estimated to be 10 to 12 years old was nearly indistinguishable from that contained in a fresh sample.

The practical consequence of such retarded degradation is that further leachate contamination resulting from fill decomposition would be moderated over a protracted length of time. In addition, the formation and migration of gases associated with decomposition would be minimized.

Attenuation by Soil Percolation

The capacity of soil percolation to rapidly decrease the concentration of potential pollutants has been documented in the literature, as well as by lysimeter work conducted in conjunction with the West Carrollton landfill study (9). Results summarized in Table 7 show the proportion of the applied constituent mass retained within the 3-ft soil columns over an approximate 5-month application period at rates approximating field conditions. Soil varieties evaluated included sand, clay, and organic loam. The last was investigated under aerobic and anaerobic conditions.

All soil columns exhibited excellent organic removal, though sand appeared slightly less efficient. In all cases, an acclimation period was necessary before highest removal efficiencies were obtained. None of the 3-ft soil columns gave any indication that organic removal capacity was becoming exhausted over the 160-day observation period. Anaerobic conditions were observed to be less efficient than aerobic conditions for organic removal. All soil columns showed some capacity to attenuate inorganic constituents. However, with the exception of clay, all columns demonstrated a decreasing capacity to do so over the duration of the study.

In all, it was the conclusion of that study that passage of leachate through a minimal depth of natural soil would render the percolate innocuous. In addition, the relative impermeability of the high ash sludge and the decreasing rate of leachate flow associated with fill consolidation exert a moderating effect upon the quantity of leachate percolating to the groundwater. Impermeability would further minimize rainfall infiltration of the landfill as a potential leachate source. However, in such a case, caution would have to be exercised to prevent runoff and subsequent drainage into surface waters.

Summary

Substances most likely to prove objectionable should high-ash-sludge leachates become a part of the groundwater would include dissolved organic matter, mineral salts, and hardness. Concentrations were within the broad range of those reported for leachates originating in landfills of municipal refuse. However, on a mass basis, leachate constituents associated with the high-ash sludge were significantly less. (Moreover, sludge composition is such as not to constitute a hazard to public health.)

In consideration of alternate approaches to protection of groundwater sources from the intrusion of leachate constitutents, the demonstrated capacity of soil percolation to effect a degree of renovation equivalent or superior to conventional treatment technology merits attention. As such, a parallel exists with the land application of wastewaters, an approach which has received national focus as an effluent management strategy. The suitability of percolation is advanced contingent upon the existence or provision of a suitable soil of sufficient depth and distribution prior to groundwater utilization to provide the necessary renovations at anticipated hydrologic conditions.

The nature of high-ash sludges is such that inherent impermeability minimizes leachate formation. The opportunity also exists for minimizing the quantity of leachate to be renovated by further sludge dewatering consistent with technological capability. The options available are sufficient to justify any selection on a case-by-case basis as opposed to a single universal approach to groundwater protection from landfill leachate intrusion.

CURRENT LANDFILL PRACTICE

Landfill practice can be expected to receive increasing attention of regulatory agencies. In addition, overall solid waste management will likely constitute a significant aspect of activities carried out under the regional planning provisions of the Federal Water Pollution Act Amendments of 1972. Commonly encountered requirements for the regulation of industrial process landfills have been previously outlined by McKeown (4). McKeown further stated that restrictions on the siting of landfills are largely oriented toward minimizing the potential for leachate contamination of ground and surface waters, as well as avoiding public nuisance. Such provisions, for example, manifest themselves as requirements that:

a. The disposal site be a minimum of 2 to 5 ft. above groundwater.

b. The site be 50 ft. above a floodplain.

c. The site be a minimum of 1 mile from a public well.

d. The site be at least 300 ft. from watercourse.

e. All subsurface conduits be removed (i.e., culverts, gas and water lines, etc.).

f. The minimum distance to a highway be 1000 ft.

g. The nearest property line be 20 ft. from the site.

A notable distinction between the operating requirements imposed upon municipal sanitary landfills and those of paper-mill origin is the necessity for daily application of cover material. In the former case, compaction and daily cover is necessary for:

a. Controlling the breeding of vermin.

b. Discouraging the entrance of rodents.

c. Preventing scavengers from feeding upon the wastes.

d. Control of gas movement.

e. Retarding rainfall infiltration of the fill.

f. Prevention of fire.

It is evident from the composition of and known behavior of paper-mill sludges that such latter precautions are unnecessary. Moreover, their properties are such that they have an inherent ability to fulfill many of the functions required of the cover material. Not only are paper-mill sludge landfills normally exempted from daily cover requirements, the precedent exists for their being utilized as a daily cover for sanitary landfills.

Prior to the issuance of a permit for operation of an industrial solid waste disposal system, a number of states require that the entire waste management plan be reviewed for conformity to sound engineering practice. Examples of provisions for design and operation that have been advanced for inclusion in plans requiring regulatory agency approval are as follows:

a. General: Map or aerial photograph of the area showing land use and zoning adjacent to the proposed disposal operation. The map or aerial photograph should show all homes, industrial buildings, wells, watercourses, dry runs, rock outcroppings, and roads. General topography should also be identified.

b. Geological Considerations: Geological examination of the proposed area is a useful adjunct to siting. Soil borings of sufficient number and depth should be taken to provide a subsurface investigation representative of the entire site. Such tests are made to determine the porosity and permeability of the soil in the landfill area. Sites with low permeability are usually preferred. General path and rate of flow of groundwater flow should be estimated.

c. Groundwater Testing: Both the level and quality of groundwater are determined using test wells or pits. Sampling to include seasonal variation is suggested. (Test wells can later be used to check groundwater quality after site is operative.) Wells are usually to be placed upstream and downstream of the projected groundwater flow pattern at varying levels.

d. Rivulet Diversion: The impact of the fill upon area drainage patterns should be considered. Natural drainage paths may be rerouted, or in some cases covered and protected from landfill runoff. Natural springs may also require rerouting. Surface drainage from the completed fill should also be considered.

e. Development of a proposed plot plan of the site showing dimensions, location and ground surface elevation of soil borings, original and proposed final land contours, proposed trenching plan or original fill face, existing and proposed drainage patterns, access roads and any fencing.

    (1) Fencing should be considered if site is near public roads or population and open to easy access. Lighting should be considered, especially if nighttime delivery is planned.

    (2) Roads should be planned based upon the expected life of the site and types and loadings of trucks and frequency of delivery. If

traffic routes include public roads through populated areas, some thought is usually given to scheduling vehicles to provide minimum neighborhood disturbance, especially when steep grades are involved. The potential for erosion and dust problems within the landfill site warrant attention.

(3) Final Grade: Consideration should be given to planning for future use of the land after the site has consolidated naturally.

f. Equipment and Operational Requirements: Heavy duty dump trucks and spreading equipment are necessary. The amount of sludge and size of storage pads will dictate the types and sizes of trucks to be used. A number of mills store sludge for delivery during daylight hours. Storage is usually upon a concrete apron protected from receiving excessive rainfall. Front-end loaders are used to clear the apron into trucks during daylight. Storage volume should be designed to accumulate sludge during particularly inclement weather. Snow removal and road clearance equipment are obvious requirements in cold climate.

g. Thought should also be given to development of such information as sludge composition, moisture content, anticipated quantities, degradability, and potential leachate properties.

Implicit in fulfilling a number of the previously cited considerations is a knowledge of the rate and extent of landfill consolidation and behavior.

SECTION II

RETAINING STRUCTURES

The basic objective of engineering sludge disposal landfills is to compress (consolidate) and confine the material and stabilize its behavior. By consolidating the material, its strength is increased many times and it becomes a stable solid that will stand as an embankment. The available landfill volume will be increased by the difference between the volume of freshly placed sludge and the amount of consolidation, and by the ability to construct high mounds of consolidated material.

NEED FOR SLUDGE CONFINEMENT AND SURCHARGE

In order to best achieve the objective, the sludge material must be contained and physically consolidated. Temporary dikes are required to laterally contain the material, and surcharge loads are required to induce consolidation by forcing water from the material. Surcharge loads are necessary for two important reasons:

a. Sludge has a tendency to hold or retain water because of its composition and may be only slightly free-draining (6, 9, 15). Therefore, surcharge loads are required to sufficiently increase the water pressure internal to the sludge material such that the water will flow out from the material. This dispersion of water will therefore allow the material to consolidate to a lesser volume. The decrease of volume is approximately equal to the volume of water dispelled.

b. Surcharge loads accelerate consolidation, thereby significantly decreasing the time required for a given total consolidation to occur. Pulp and paper-mill sludge is similar to an organic soil called peat. For some peats, the time for consolidation has been shown to be accelerated by surcharge, by a factor of thousands (25). For example, a 10-ft-thick layer of peat that would take 30 years to consolidate could theoretically be consolidated in 10 days by the proper use of a surcharge load.

Because of the initial high water content and low strength of fresh sludge, the initial surcharge thickness probably should not exceed about 3 ft. (This recommendation is based on field experiences with peat discussed in Reference 25.) Greater initial thickness may cause failure of the sludge from a shear strength and bearing capacity (ability to support load) consideration. If, when placing the 3 ft of surcharge, lack of the sludge material to support it is evident, the surcharge thickness should be reduced to a supportable amount. However, some type of membrane or mat may be used to supply support without reducing thickness of the surcharge. (Membranes are discussed under Suggested Construction, page 22.) If greater surcharge thickness is desired in order to induce a larger amount of consolidation and/or further decrease the time element, the following recommendations are made:

a. Bearing capacity of the sludge material should be checked (25, 26, or 27, or 28).

b. Application of the surcharge could be made in stages (layers) if the sludge-bearing capacity is not sufficient. Between each stage, time (weeks) should be allowed to elapse such that an amount of consolidation would occur. Consolidation causes the material to increase in strength, thereby allowing it to support greater loads. Therefore, each increment of consolidation between surcharge stages increases the strength for the next load. (Calculation of consolidatio and time rates will be covered under Consolidation, Settlement, and Slope Stability, page 24.)

c. A membrane or mat could be used to increase the sludge supporting ability, thereby allowing greater surcharge loads. Obviously, a membrane or mat could be used in conjunction with stage construction.

The economics involved with the use of greater surcharge loads should be balanced against the benefits gained from increased usable landfill volume and accelerated consolidation time. The most economical material to use for the dikes and surcharge loads would be earth material existing at or near the landfill site.

DRAINAGE

Drainage is a highly important factor that must be considered for the following reasons:

a. A large volume of water will be forced out of the sludge material. The sludge and water will be contained within the dike-enclosed area; therefore, adequate drainage of the water from the enclosed area must be accomplished.

b. The time rate of consolidation is theoretically related to the square of the shortest drainage path through a material. Therefore, by adequately controlling the distance or thickness through which a material must drain, the consolidation time can be accelerated by a factor of hundreds. For example, a material of constant properties that is drained through a 10-ft thickness could theoretically have its consolidation time accelerated by a factor of 400 if it was drained through two 5-ft thicknesses. In other words, if the 10-ft drainage path resulted in 30 years for an amount of consolidation to occur, the 5-ft drainage paths would allow the same consolidation to occur in 27 days.

In order to accomplish drainage from the enclosed area and to accelerate consolidation, drainage blankets should be utilized. If contamination of the groundwater could be a problem, appropriate action should be taken (discussed previously on page 9). The drainage blankets should consist of clean sands and/or gravels and should be about 1 ft of uniform thickness extending over the entire enclosed dike area. Outlets through the dike for the drainage blankets must be provided. A water collection pocket about 3 to 4 ft long consisting of gravel, intersecting each drainage blanket, and tapped with a pipe no smaller than 6 to 8 in. should provide adequate drainage. Drainpipes should extend out from the dike a sufficient amount so that discharge will not erode the dike. The drainage blankets should be placed in the bottom of the enclosed fill area (if the elevations are such that it will drain the enclosed area), not less than every 8 to 10 ft of fresh sludge material, and at the top of the fill prior to placement of the surcharge load. If no drainage blanket can be used at the bottom of the fill, the first blanket should be about 5 ft above the bottom of fill. The above-mentioned drainage blanket spacings allow vertical drainage paths of about 4 to 5 ft in each sludge layer.

Shown in Figure 5 is a cross section of a dike and a portion of sludge fill illustrating the use of a dike, drainage blankets, water collection pockets, drainpipes, and surcharge load. If the landfill site has a solid foundation (such as an old rock quarry) so that deformation or consolidation beneath the sludge fill will be negligible, the middle drainpipe of Figure 5 could be eliminated. However, the middle drainage blanket would have to be connected to the lower blanket. This connection could be made by a 5- to 10-ft-wide by 1-ft-thick layer of sand or gravel on the dike slope. The full surcharge load should not extend to the dike, because the less thick sludge on the dike slope will consolidate more than that away from the slope. Water from the fill area can be channeled or collected from the drainpipes and disposed of as necessary.

POSSIBLE PLAN FOR LANDFILL AREAS

Assume that a large landfill site is available and that several confinement areas are required to cover it. One possible system of progressively constructing and filling enclosed areas is presented in Figure 6 with the following recommendations:

a. In order to adequately maintain drainage of each new enclosed area, the areas should start in the center of the landfill site and progress outward.

b. New enclosed areas adjacent to old ones should have their drainage blankets connected to the older area ones. This connection can be either a direct intersection in the case of the older dikes being removed or through the existing drainage pipes in the case of the older dikes not being removed. Drainage of the older fill areas should be allowed to continue, because of slow continuing consolidation or new consolidation induced by sludge being placed on top of the old.

c. After the sludge consolidation of an enclosed area, the earth dikes may or may not be removed. The choice of removal should be based on an economic consideration involving the following factors:

(1) Availability and cost of earth materials for new dikes.

(2) Cost of removing old dikes and constructing new ones from the old materials versus using new materials.

(3) The sludge fill volume gained by removing the dikes.

d. The choice of removing and reusing surcharge material after sludge consolidation should be based on economic factors similar to the preceding ones. However, if fresh sludge is to be placed on top of consolidated sludge, part or all of the existing surcharge materials may be desired as a supporting surface for construction equipment and trucks. The need for a supporting material would depend on the strength (ability) of the consolidated sludge to support the equipment. If the surcharge material is removed and supporting material is needed for equipment, an earth material road could be placed on the consolidated sludge.

e. If surcharge materials are removed, the top drainage blanket materials may also be reused for another area. The cost of sand or gravel drainage materials may justify removal of the surcharge loads.

f. If sludge disposal is to continue upward, the surcharge material may be used for constructing the new enclosing dikes after consolidation of the lower sludge. The top drainage blanket then becomes the bottom drainage blanket for the fresh sludge. An upper disposal area should not begin until at least adjacent lower areas have been filled and partially consolidated.

As can be seen in Figure 6, planning the arrangement and construction sequence of enclosing areas results in only one dike side needed for some areas. Planning also results in efficient use and reuse of materials.

CONSTRUCTION CONSIDERATIONS

Enclosed area dimensions, dike construction, and sludge placement methods will be directly controlled by the consistency of the sludge material. For convenience, sludges will be divided into two very general behavior categories: fluid behavior and plastic behavior. A fluid-type sludge will tend to flow in a viscous slurry when unconfined. A plastic-type sludge will not flow but will form a self-supporting mound when unconfined and will have a dry appearance.

Fluid and semiplastic type sludges will limit one of the enclosed area dimensions because they will have to be spread and leveled with a crane dragline or similar equipment working from the dike. Drainage blankets and probably the surcharge material will also have to be spread with the dragline due to the sludge not being able to support equipment. One dimension of the enclosed area must be limited to twice the working length of a dragline. (The average dragline working length is about 45 to 50 ft.) This limit will allow a dragline to reach the center of the area from either of two dike sides. The limit dimension of 90 to 100 ft is measured from the inside edges at the top of the proposed dikes. An inside dike slope of 45 deg (1:1) is a good inclination angle for design and construction.

An enclosed area does not have to be a square; it could be rectangular or any other shape. However, the above-mentioned limitation specifies that the shortest dimension be about 50 ft from the center to a dike side. A rectangular area would be limited to about 100 ft in width but could be any length. Due to the deficiency of knowledge and experience concerning the plastic-type sludges and knowing they are initially low in strength, the above-mentioned limitation **seems reasonable for all sludges. If equipment for** placing plastic sludge cannot operate directly on the fresh material, a dragline from a dike side would have to be used.

Assume here that sufficient earth materials for the dikes and surcharge loads are available at the landfill site. If the area to be enclosed does not have an approximately level surface, some material for the dikes can be obtained by leveling the area with a bulldozer. The area can also be excavated to obtain dike and surcharge materials. However, excavation should not be so deep that water would not drain from the bottom or first drainage blanket. Further assume that the site has now been prepared consistent with the discussion on page 16 and the bottom drainage blanket (if there is to be one) and drainpipes have been placed.

With the assumptions above and for a fluid-type sludge, the following suggestions for possible construction are made:

a. Begin the earth dike construction by bulldozing a 4- to 5-ft height around the sides of the fill area, maintaining the design enclosed dimensions and slope. Some compaction of the dike material is achieved from the tractor. The outside dike slope could be as-constructed but with a section of low inclination angle in order to allow a ramp for equipment and trucks to get to the top of the dike. If sludge is to be brought in by trucks, an opening in the dike could be left on one side for the trucks. The trucks could also dump from the dike, or the sludge could be piped into the fill area. Care should be taken not to disrupt the bottom drainage blanket. A dragline, working from the dike sides, would be needed to spread the sludge.

b. With the first 4 to 5 ft of sludge in place, a drainage blanket and drainpipes would be needed if they were not placed at the bottom. (However, assume they are at the bottom.) The dike construction could now continue for another 4 to 5 ft in height, and it could be widened as necessary to provide a convenient width for equipment. Sludge would now be placed again by truck or pipes and spread by the dragline. The operations would continue until a sludge design thickness was reached, at which point another drainage blanket would be required.

c. The sludge surface should be approximately level, and this could be done by the dragline pulling a raft across the surface. A raft could be made by lacing together several logs, poles, pipes, etc. The gravel drain pockets, drainpipes, and drainage blanket should now be placed. Depending on the strength of the sludge, the following procedures could be used for placing the drainage blanket:

(1) If the sludge would support the drainage blanket material plus a small lightweight tractor with extra track width, the blanket could be placed by the tractor spreading material ahead of itself.

(2) If the sludge would support the drainage blanket only, then the material could be placed, spread, and leveled by the dragline.

(3) If the sludge would not support the drainage blanket, some kind of porous membrane or mat for support would have to be used on top of the sludge. Drainage blanket material could then be placed by the above-mentioned methods. Porous membranes are materials such as burlap, wire mesh sheets, special plastic sheets (such as in Reference 29), possible porous paper sheets, etc.

d. Construction of the fill area should continue for the upper sludge layers as in the previous steps. At the top of the fill, a drainage blanket and surcharge must be placed. Methods for placing these would be the same as in c, above. Figure 7 illustrates, in general, the above-suggested fill area construction steps.

For a plastic-type sludge, construction of an enclosed fill area may be simpler. The above-mentioned steps should be followed in general. However, if a lightweight tractor can operate on top of the sludge, placement could be made with the tractor and in thicker layers. Also, if a tractor could be used, no problems would occur in placing drainage blankets and surcharge loads. If the sludge will not support a tractor, then the construction steps for a fluid-type sludge would have to be followed.

SECTION III

CONSOLIDATION, SETTLEMENT, AND SLOPE STABILITY

CONSOLIDATION THEORY

Pulp and paper-mill sludge consists of solid constituents between which are spaces (voids) filled with air or water. The void space of the sludge in the fill (or, in another sense, the sludge density), the amount of water contained in the void spaces (water content), and the sludge permeability are of concern, because these affect the strength and settlement (vertical displacement) of the sludge. Figure 8 is a summary of weight and volume relations for a sludge sample. Appendix B presents the laboratory test procedures for determining the physical properties necessary in understanding and predicting the behavior of sludge.

Most sludges will be 100 percent saturated (all void space filled with water). If a saturated sample is subjected to a one-dimensional load (Figure 9), the decrease in volume is accomplished by water being squeezed from the voids at a rate controlled by the sludge permeability. This process is termed consolidation. The change in height, ΔH , per unit of original height, H , equals the change in volume, ΔV , per unit of original volume, V .

$$\frac{\Delta H}{H_1} = \frac{\Delta V}{V_1}$$

ΔV can be expressed in terms of void ratio, e , and ΔH becomes

$$\Delta H = H_1 \left(\frac{\Delta e}{1 + e_1} \right) = H_1 \left[\frac{(e_1 - e_2)}{1 + e_1} \right]$$

This relation is for primary compression, which is due entirely to the decrease of water volume. Secondary compression occurs after primary compression and may be related to a plastic creep deformation and compression of the constituent particles. The rate of consolidation can also be calculated. The prediction of the rate of consolidation usually has the largest error because of changing consolidation parameters, secondary compression, and construction rate (increasing load rate). Detailed discussion of consolidation theories can be found in References 7-9. Stress-strain characteristics of sludge can be determined in the laboratory (Appendix B) and applied together with the consolidation theory to predict sludge settlement and rate for landfills.

SETTLEMENT PREDICTION

Vertical Stresses

The vertical stress acting on a horizontal plane at depth, z, is equal to the weight of all matter that rests above the plane. If the unit weight of the matter is constant with depth, the stress at depth, z, is equal to the depth multiplied by the wet unit weight, γ_m (Appendix B, Unit Weights). A load-depth diagram is usually constructed by plotting stress versus depth as in Figure 10. The total initial stress, P_o, at any depth may be obtained from the diagram. Sludge materials have extremely high water contents and large volumes of water. When placed in a contained landfill, a pond of water is essentially created and the sludge constituents are held in suspension. The water exerts a hydrostatic pressure, u (Figure 10), as a function of depth, on the sludge constituents. As a result of the hydrostatic pressure, the effective contact stress, P'_o, between sludge particles is reduced by the magnitude of u (Figure 10). In other words, the sludge particles support a load of $P_o - u$ only. The average vertical stress within a layer acts very close to the middepth of the layer; therefore, it may be taken at the middepth point with negligible error (about 10 percent). In Figure 10, the average effective stress in the sludge layer is $P'_o = 138\ \text{lb/ft}^2$. In Figure 11, if a load ΔP is added to the sludge layer of Figure 10, the resulting effective stress is $P'_o + \Delta P$, and the average stress is $P' = (138 + \Delta P)\ \text{lb/ft}^2$.

Settlement

Once data from laboratory tests (Appendix B) and from stress analysis are available, the settlements for a landfill design can be easily obtained. In order to make settlement computations, a landfill design height and the number of layers should be selected. From the laboratory tests, sludge wet unit weight, γ_m, has been determined and the average initial effective stress, P'_o, for each design sludge layer can be calculated. The total load, ΔP, above each sludge layer can now be calculated (for sand, $\gamma_m \approx 100\ \text{lb/ft}^3$; for surcharge, $\gamma_m \approx 120\ \text{lb/ft}^3$). Total load, ΔP, equals the wet weight of all sludge, sand, and surcharge layers above the one being considered. The primary settlement, ΔH_{pri}, for a sludge layer is computed by the equation

$$\Delta H_{pri} = \frac{C_c H_t}{1 + e_o} \left(\log_{10} \frac{P'_o + \Delta P}{P'_o} \right)$$

where ΔH_{pri} = primary settlement

C_c = compression index determined from laboratory tests (Appendix B, Consolidation Test), Plate B-13. (If the laboratory pressure-void ratio plot is curved and P' corresponds to a laboratory pressure in the curved region, C_c should be taken as the tangent at the point $P \approx P'$.)

H_t = total initial thickness of the sludge layer. In Figure 11, $H_t = 2H$

e_o = initial void ratio existing at P'_o , obtained from laboratory tests (Appendix B, Consolidation Test), Plate B-13.

P'_o = average initial effective stress within the sludge layer, as previously described

ΔP = total load above the sludge layer, as previously described

To compute settlement from secondary compression following primary consolidation, use the following equation:

$$\Delta H_{sec} = C_a H_t \log_{10} \frac{t_{sec}}{t_{pri}}$$

where ΔH_{sec} = settlement from secondary compression

C_a = coefficient of secondary compression obtained from the laboratory tests (Appendix B, Consolidation Test) (Plate B-12) for the total laboratory load increment corresponding to P' in the field

t_{sec} = time for which settlement is significant

t_{pri} = time to completion of 100 percent primary consolidation

For one cycle of log time

$$\Delta H_{sec} = C_a H_t \log_{10} (10)$$

$$\Delta H_{sec} = C_a H_t$$

Total settlement is equal to

$$\Delta H_{total} = \Delta H_{pri} + \Delta H_{sec}$$

If sludge materials having largely different compression indexes are placed within a layer, the settlement of the total sludge layer can be calculated by the following equation:

$$\Delta H_{total} = \Delta H_{1_{total}} + \Delta H_{2_{total}} \ldots + \Delta H_{n_{total}} = \sum_{1}^{n} \Delta H_n$$

where n = individual layers of different sludge within a single layer of sludge

Time rate of settlement is computed by the following equation for primary consolidation:

$$t_{pri} = \frac{TH^2}{C_v}$$

where t_{pri} = time for primary consolidation in the field

T = dimensionless time factor related to the percentage, U, of primary consolidation. Figure 12 is a curve for T versus U from which values of T can be obtained

H = length of longest vertical path for drainage of water. For drainage to pervious layers at top and bottom of the sludge layer, $H = H_t/2$. For drainage to only one pervious layer, $H = H_t$

C_v = coefficient of consolidation determined from the laboratory tests (Appendix B, Consolidation Test) (Plate B-12) for the total laboratory load increment corresponding to P' in the field.

Primary settlement time rate, t_{pri}, can also be determined from the nomograph in Figure 13. Figures 12 and 13 correspond to instantaneous load applications.

If load ΔP application is gradual and construction time is appreciable compared with time required for primary consolidation, the time factor curves of Figure 14 should be used to obtain the T values for the field time, t_{pri}, equation. (Figure 14 is strongly recommended to be used at all times.) In Figure 14, T_o is determined from

$$T_o = \frac{C_v t_o}{H^2}$$

where t_o = end of construction time. t_o can be estimated from the volume, V_f, of the landfill and the pulp and paper-mill sludge production rate, V_s/day

$$t_o = \frac{V_f}{V_s} \text{ in days}$$

T and U during construction (prior to t_o) are given by the upper enveloping dashed curve to the point of calculated T_o. After the end of construction time t_o, T and U are given by the dashed curve corresponding to T_o.

The time for secondary consolidation is t_{sec}, as defined previously. If one cycle of log time is used for computing ΔH_{sec}, $t_{sec} = 10 \times t_{pri}$.

The time for total settlement to occur is

$$t_{total} = t_{100\text{ percent pri}} + t_{sec}$$

where t_{total} = time for total settlement to occur

$t_{100 \text{ percent pri}}$ = time for 100 percent primary settlement to occur

t_{sec} = chosen time over which to compute the amount of secondary settlement

For a layer of sludge with materials having largely different coefficients of consolidations, use an average C_v for the time computations. Settlement time plots (Plate 1 is a suggested form) should be made for the sludge layers of a landfill. The curves will show the importance of time and will indicate when retaining dikes could possibly be removed. Dikes can be removed after about 90 percent total settlement has occurred.

Possible Errors

Sources of error for both consolidation and time rate predictions are listed below.

a. Nonrepresentative laboratory specimens.

b. Inaccurate laboratory data.

c. Nonhomogeneous sludge material within the layers.

d. Decreasing coefficient of permeability with consolidation.

e. Construction rate cannot be accurately considered.

f. Inaccurate load estimate, ΔP . The actual thickness of the layers will vary from design, because the lower layers will consolidate as the upper layers are constructed. Therefore, greater thickness of upper layers will result.

g. Change in sludge material properties as a result of construction and consolidation.

SLOPE FAILURE CONDITIONS

After consolidaton of the sludge layers in a dike-enclosed area, the dikes may be left in place or removed. If the dike material and the dike-occupied space are not needed for continuation of sludge disposal, they may remain permanently and eventually be covered with sludge. However, if the space occupied by the dike and the dike material are required for landfill continuation, the stability of the consolidation sludge upon removal of the dike will have to be considered. Three approaches may be taken: (a) the sludge may be allowed to form a natural slope, (b) a slope having an angle of 45 to 50 deg may be cut, or (c) a slope may be designed to prevent movement and breaking off of material.

When landfill interior dikes are removed, sludge will be placed against the natural or cut slope; therefore, the sludge material that may have fallen will not be a problem. If dikes along a landfill periphery are removed, safe slopes should be designed. When sludge disposal is to continue upward, the upper dikes should not be so close to a lower layer sludge slope as to cause failure. Slope stability should be checked in order to design a safe distance between an upper dike and a slope.

Failure of a slope or embankment is the rapid or gradual displacement of a portion of the embankment relative to the remainder of the mass. The portion that moves may do so as a slide, a rotation, or a displacement of a wedge shape. Failures follow changes in shear stress or shear strength that lead to unbalanced driving forces. Imbalance of forces is caused by changes in slope profile, increase in water pressure, added weight to the top of the slope, or time-conditioned decrease in shear strength due to weathering, leaching, mineralogical changes, opening and softening of fissures (cracks), or continuing gradual shear strain. The possibility of movement occurring is evaluated by comparing forces resisting failure with those causing failure. This ratio is the safety factor.

Slope Design Considerations and Stability Analysis

Because of the sand drainage blankets between sludge layers, failure is most likely to be in the form of a wedge of sludge material displacing with translational motion along or through a sand layer. The slip or failure surface will be a composite slip surface through the sludge and along the sand layer. Analysis of a failure of the above-mentioned type can be made using a procedure of slices and a composite slip surface (8). The analysis method presented below is based on total stress and not on effective stress, because pore pressures within sludge will not be known.

In order to design a safe slope, a slope angle is assumed and the minimum factor of safety is calculated. The procedure is repeated for other assumed slope angles until a satisfactory or design factor of safety is acquired. Once the design factor of safety is obtained, the corresponding slope angle is the angle at which the sludge slope should be cut. Because the analysis procedure is based on total streases, a minimum design factor of safety of about 1.5 for landfill interior sludge slopes against which sludge will eventually be placed seems reasonable. A minimum design factor of safety is the value at and below which a failure might possibly occur. For landfill periphery sludge slopes which should have a long duration and because of total stress analysis, the design factor of safety of about 2.0 seems reasonable.

Design and analysis procedures for consolidated sludge slopes are as follows:

a. Choose a trial slope angle, β, as shown in Figure 15. A β between 45 and 50 deg would be a good starting point.

b. Choose a trial slip (failure) surface such as trial 1 in Figure 15. Because total stress analysis is being used and the sludge material is initially undrained when a slope is cut, the sludge angle of internal fraction, ϕ, is equal to 0. Therefore, the slip surface through the sludge layers can always be taken at an angle $\alpha_2 = 45$ deg. The slip surface angle through the sand layers and through the surcharge material is $\alpha_1 = 45 \text{ deg} + \phi/2$. A good approximate friction angle, ϕ , for the sand and surcharge is $\phi = 30$ deg; therefore, $\alpha_1 = 60$ deg. For the trial 1 slip surface, there is no angle α_3 . However, for the other trial slip surfaces shown, α_3 and α_4 are determined (as shown in Figure 15) by the location of the trial slip surfaces through the sludges.

c. Divide the sliding mass into slices. For convenience, the slices can be taken at points separating zones of different material properties or at points where a break occurs in the upper or lower boundary of the sliding mass as shown in Figure 15.

d. Set up a table as shown below and fill it in (8).

Tabular Computation

	Values from the Cross Section					Computed Values			
Slice No.	tan α	Δx ft	P psf	S_U psf	ϕ deg	B_o	A'_o	N_a	A_o
1									
2									
3									
4									
.									
.									
.									

Note that α = angle at base of slice

Δx = slice width, ft

P = average vertical total stress on base of slice (γ_m × depth to center point of slice base). γ_m (Appendix B, Unit Weights) average for each sludge layer can be obtained from the average water content, w_{avg} (Appendix B, Solids and Water Contents) for each layer as

$$\gamma_{m_{avg}} = (1 + w_{avg}) \left(\frac{\gamma_w}{w_{avg} + \frac{1}{G_s}} \right)$$

G_s = specific gravity of solids (Appendix B, Specific Gravity). The average water contents can be determined from the material adhering to the vane shear test device (Appendix B, Vane Shear Test). The equation above assumes 100 percent saturation of the sludge.

$S_U = S_{U_{vane}}$ (Appendix B, Vane Shear Test) $\times\ \mu$ = average undrained sludge shear strength at base of slice. μ = correction factor from Figure 16.

ϕ = angle of internal friction for the sand and surcharge

$B_o = P \times \tan\alpha \times \Delta X$

$A'_o = S_U \times \Delta X$ for sludge base. $A'_o = P \times \tan\phi \times \Delta X$ for sand and surcharge base

$N_a = 1.0$ for sludge base

$N_a = \cos^2\alpha \left(1 + \frac{\tan\alpha \tan\phi}{F}\right)$ for sand and surcharge base

$A_o = \frac{A'_o}{N_a}$

Calculate the summations of the B_o and A_o columns, $\sum B_o$ and $\sum A_o$

e. Calculate the factor of safety, F , by successive approximations or by solving for F in the equation

$$F = \frac{\sum A_o}{\sum B_o}$$

Successive approximations or solution for F are required, because F appears on both sides of the equation above.

f. Repeat steps b through e taking different trial slip surfaces until the minimum factor of safety is found for trial slope angle β .

g. Choose other trial slope angles, β , and find their minimum factors of safety by steps a through f.

h. For interior landfill sludge slopes, the β with a corresponding F greater than 1.5 would be a good design slope. For periphery landfill sludge slopes, the β with a corresponding F about 2.0 would be a good design slope.

The field experimental example presented in the next section should help clarify some of the procedures described above.

SECTION IV

FIELD EXPERIMENTAL EXAMPLE

RETAINING STRUCTURES AND SLUDGE PLACEMENT

An experimental paper-mill sludge landfill was constructed and monitored during the period 1971-1972 (6-9, 30, 31) to obtain engineering information essential to developing procedures for the design and operation of pulp and paper-mill waste landfills. The work was sponsored by the EPA and NCASI. Kimberly-Clark Corporation-Morraine Mill, West Carrollton, Ohio, provided the landfill site and dewatered sludge. The landfill site was an old gravel pit near West Carrollton. The experimental fill consisted of two sludge layers, initially 10 ft thick, with 1-ft-thick sand drainage blankets at the top, middle, and bottom. An earth dike provided lateral confinement of the sludge, and a surcharge load consisting of 3 ft of natural soil was used. A lysimeter study provided information on changes in quality of the leachate when passed through selected natural soils. Figures 17 and 18 show the landfill in a plan view and typical cross section, respectively.

For the dike construction, a 35-ton Link Belt power shovel was used for the excavation work and a D-6 Caterpillar tractor was used to move the excavated earth material and shape the dikes. The dike sides were constructed with one corner left low for placing sand in the fill bottom. After spreading sand for the lower drainage blanket, the dike was closed and sludge was dumped from trucks over the west and south dike walls. Even though the sludge exhibited a plastic behavior, it would not support the D-6 tractor. Therefore, the power shovel was converted into a dragline unit and proved ideal for spreading the sludge. A lightweight tractor with extra-wide tracks was obtained, but it arrived too late for use in spreading the lower sludge layer and because the dike had been fully constructed, it was not used for the upper sludge layer.

When the lower layer of sludge was sufficiently thick, it was leveled with the dragline by dragging two telephone poles cabled together across the surface. Sand for the middle drainage blanket was then dumped along one dike wall, distributed by the dragline, and leveled with the dragline/telephone pole arrangement. The lightweight tractor was not used with the middle sand blanket because the dikes had been completed, and manuevering the tractor in and out of the field would have been difficult.

When the upper sludge layer reached the desired thickness, it too was leveled by dragging the telephone poles. Sand was dumped along one dike wall and was spread by the lightweight tractor pushing the sand ahead of its path. Because the sand acted as a supporting mat, the small tractor had no difficulty in working on the landfill surface. Sand placement with the small tractor was faster than with the dragline. Both the D-6 and small tractor were used for spreading the earth surcharge material. The surcharge material was dumped onto the landfill surface by the dragline.

SLUDGE MATERIAL

The dewatered sludge used in the landfill had the physical properties shown in Table 8. These properties were determined from samples taken at various elevations as the sludge was placed; determinations were made in accordance with the tests described in Appendix B. Therefore, the properties represent the initial, as-placed sludge conditions.

CONSOLIDATION AND SETTLEMENT

Figures 10 and 11 give the initial average effective stress, $P'_o = 138$ lb/ft^2 (discussed in Section III) for each 10-ft-thick layer. The total load acting on the lower sludge layer, ΔP_{lower}, is calculated as follows:

a. Weight of sludge (design thickness) above lower layer $= 10 \text{ ft} \times 70 \text{ lb/ft}^3 = 700 \text{ lb/ft}^2$

b. Top sand layer weight $= 1 \text{ ft} \times 100 \text{ lb/ft}^3 = 100 \text{ lb/ft}^2$

c. Surcharge weight $= 3 \text{ ft} \times 130 \text{ lb/ft}^3 = 390 \text{ lb/ft}^2$

d. $\Delta P_{lower} = (700 + 100 + 390) \text{ lb/ft}^2 = 1190 \text{ lb/ft}^2$

e. Average effective stress $P'_{lower} = P'_o + \Delta P_{lower} = (138 + 1190) \text{ lb/ft}^2$ $= 1328 \text{ lb/ft}^2 = 0.664 \text{ ton/ft}^2 \approx 0.664 \text{ kg/cm}^2$

The total load acting on the upper layer, ΔP_{upper}, is the weight of the sand blanket and surcharge. The sand blanket weight is included in P'_o. Therefore, $\Delta P_{upper} = 3 \text{ ft} \times 130 \text{ lb/ft}^3 = 390 \text{ lb/ft}^2$ = surcharge weight. The average effective stress is $P'_{upper} = P'_o + \Delta P_{upper} = (138 + 390) \text{ lb/ft}^2$ $= 528 \text{ lb/ft}^2 = 0.264 \text{ ton/ft}^2 \approx 0.264 \text{ kg/cm}^2$.

Figure 19 shows the consolidation characteristics (discussed in Section III) for the sludge used in the experimental landfill. Using the settlement equation

$$\Delta H_{pri} = \frac{C_c H_t}{1 + e_o} \left(\log_{10} \frac{P'_o + \Delta P}{P'_o} \right)$$

defined previously in Section III, the primary settlement for each layer can be calculated as follows:

a. Lower layer properties.

$$C_c = 1.65$$

$$H_t = 10 \text{ ft}$$

$$e_o = 4.85 \quad \text{at} \quad P'_o$$

$$P'_o = 138 \text{ lb/ft}^2$$

$$\Delta P_{lower} = 1190 \text{ lb/ft}^2$$

b. $$\Delta H_{pri_{lower}} = \frac{(1.65)(10 \text{ ft})}{1 + 4.85} \left(\log_{10} \frac{1328 \text{ lb/ft}^2}{138 \text{ lb/ft}^2}\right)$$

$$= 2.82 \text{ ft} \times 0.9833$$

$$= 2.77 \text{ ft} = 33.28 \text{ in.}$$

c. Upper layer properties.

$$C_c = 1.65$$

$$H_t = 10 \text{ ft}$$

$$e_o = 4.85 \quad \text{at} \quad P'_o$$

$$P'_o = 138 \text{ lb/ft}^2$$

$$\Delta P_{upper} = 390 \text{ lb/ft}^2$$

d. $$\Delta H_{pri_{upper}} = \frac{(1.65)(10 \text{ ft})}{1 + 4.85} \left(\log_{10} \frac{528 \text{ lb/ft}^2}{138 \text{ lb/ft}^2}\right)$$

$$= 2.82 \text{ ft} \times 0.582$$

$$= 1.64 \text{ ft} = 19.72 \text{ in.}$$

Secondary settlement, defined previously in Section III as

$$\Delta H_{sec} = C_a H_t \left(\log_{10} \frac{t_{sec}}{t_{pri}}\right)$$

can be calculated as follows:

a. Lower layer $C_a = 0.018$ from Figure 19 laboratory tests corresponding to $P'_{lower} = 0.664 \text{ ton/ft}^2$.

b. $H_t = 10$ ft.

c. For one cycle of log time

$$\Delta H_{sec_{lower}} = C_a H_t$$

$$= 0.018 \times 10 \text{ ft} = 0.18 \text{ ft}$$

$$= 2.16 \text{ in.}$$

d. Upper layer $C_a = 0.016$ from Figure 19 laboratory tests corresponding to $P'_{upper} = 0.264 \text{ ton/ft}^2$.

e. $H_t = 10$ ft.

f. For one cycle of log time

$$\Delta H_{sec_{upper}} = C_a H_t$$

$$= 0.016 \times 10 \text{ ft} = 0.16 \text{ ft}$$

$$= 1.92 \text{ in.}$$

Total settlement (Section III) for the landfill is calculated as follows:

a. Lower layer $\Delta H_{total_{lower}} = \Delta H_{pri} + \Delta H_{sec} = 33.28 \text{ in.} + 2.16 \text{ in.}$
$= 35.44$ in.

b. Upper layer $\Delta H_{total_{upper}} = 19.72 \text{ in.} + 1.92 \text{ in.} = 21.64 \text{ in.}$

c. Total for the landfill

$$\Delta H_{total} = \Delta H_{total_{lower}} + \Delta H_{total_{upper}}$$

$$= 35.44 \text{ in.} + 21.64 \text{ in.} = 57.08 \text{ in.} = 4.76 \text{ ft}$$

The rate of settlement is calculated as previously defined in Section III.

For the field experimental landfill, settlement rates are calculated as follows:

a. Lower layer $C_v = 0.013 \text{ in.}^2\text{/min} = 0.13 \text{ ft}^2\text{/day}$ from Figure 19 laboratory tests corresponding to average load between 0 and P'_{lower}, which was 0.332 ton/ft^2.

b. For use of Figure 14 (Section III). Construction period from beginning to end was 62 days; therefore, take $t_o = 62$ days. This time includes the construction of the lower layer in addition to construction of the load ΔP_{lower}. Use of $t_o = 62$ days and starting the settlement-time plot (presented later on page 60) at time 0 fit the final portion of the field measured behavior data curve fairly good. The procedure above assumes that consolidation of the lower sludge layer actually begins during its construction, and fit of the predicted and field data tends to make the assumption good for times after about 40 percent of total consolidation.

c. $H = 5$ ft.

d. $T_o = \frac{C_v t_o}{H^2} = \frac{(0.13 \text{ ft}^2/\text{day})(62 \text{ days})}{25 \text{ ft}^2} = 0.3224$

e. From Figure 14.

U , percent	T
0	0
10	0.014
20	0.060
40	0.260
60	0.400
80	0.660
90	0.950
100	2.000

f. Time for primary consolidation in the field is calculated as follows:

(1) $H = 5$ ft
$C_v = 0.13$ ft^2/day

(2) $t_{pri_{lower}} = \frac{TH^2}{C_v} = T \frac{25 \text{ ft}^2_{lower}}{0.13 \text{ ft}^2/\text{day}} = T \times 192.3$ days

T	$t_{pri_{lower}}$ (days)
0	0
0.014	2.69
0.060	11.54
0.260	50.00
0.400	76.92
0.660	126.92
0.950	182.69
2.000	384.62

g. Percent consolidation in the field is calculated as follows:

$$\text{Percent } \Delta H_{pri_{lower}} = U \times \Delta H_{pri_{lower}}$$

U , percent	$\Delta H\left(\text{percent } \Delta H_{pri_{lower}}\right)$, in.
0	0
10	3.328
20	6.656
40	13.312
60	19.968
80	26.628
90	29.952
100	33.280

h. Plot time, $t_{pri_{lower}}$, versus settlement, $\left(\Delta H \text{ percent } \Delta H_{pri_{lower}}\right)$ as in Figure 20.

i. Upper layer $C_v = 0.016 \text{ in.}^2/\text{min} = 0.16 \text{ ft}^2/\text{day}$ from Figure 19 laboratory tests corresponding to average load between 0 and P'_{upper} , which was 0.132 ton/ft^2.

j. $t_o = 30$ days for upper layer construction and surcharge. $H = 5$ ft .

k. For Figure 14.

$$T_o = \frac{C_v t_o}{\text{ft}^2} = \frac{(0.16 \text{ ft}^2/\text{day})(30 \text{ days})}{25 \text{ ft}^2}$$

$$= 0.192 \approx 0.2$$

l. From Figure 14.

U , percent	T
0	0
10	0.014
20	0.060
40	0.220
60	0.340
80	0.620
90	0.900
100	2.000

m. Time for primary consolidation in the field is calculated as follows:

(1) $H = 5$ ft
$C_v = 0.16 \text{ ft}^2/\text{day}$

(2) $$t_{pri_{upper}} = \frac{TH^2}{C_v} = T \frac{25 \text{ ft}^2}{0.16 \text{ ft}^2/\text{day}} = T \times 156.25 \text{ days}$$

T	$t_{pri_{upper}}$ (days)
0	0
0.014	2.19
0.060	9.38
0.220	34.38
0.340	53.13
0.620	96.88
0.900	140.63
2.000	312.50

n. Percent consolidation in the field is calculated as follows:

$$\text{Percent } \Delta H_{pri_{upper}} = U \times \Delta H_{pri_{upper}}$$

U, percent	$\Delta H\left(\text{percent } \Delta H_{pri_{upper}}\right)$, in.
0	0
10	1.972
20	3.944
40	7.888
60	11.832
80	15.776
90	17.748
100	19.720

o. Plot time, $t_{pri_{upper}}$, versus settlement, $\Delta H\left(\text{percent } \Delta H_{pri_{upper}}\right)$ as in Figure 21. Time $t_{pri_{upper}}$ starts at the upper layer construction start time, 32-day point in Figure 21.

p. The secondary consolidation amounts and times ($10 \times t_{pri}$) for the lower and upper layers can be added to Figures 20 and 21.

The theory of consolidation assumes settlement starts as the load ΔP is added to each sludge layer. Therefore, the settlement prediction curves should have started at 32 days in Figure 20 and at 62 days in Figure 21. However, assuming, as in the previous steps, that settlement started with each layer's construction gave a better fit of the predicted and measured time rates. Had the ΔH_{total} for each layer been used instead of ΔH_{pri}, the settlement-time curves would have been closer to the measured data.

SLOPE STABILITY

A slope was cut in the consolidated sludge material in order to investigate the applicability of stability analysis. Failure occurred in the slope, and the composite slip surface analysis was found to be the most applicable. Prior to cutting the slope, vane shear tests (Appendix B, Vane Shear Test) were conducted, and results are shown in Figure 22 for both undisturbed and remolded conditions.

Figure 23 shows a cross section for the cut slope and the approximate zone of failure. Material moved out of the slope about 5 to 6 ft back from the top of the original cut. However, surface tension cracks occurred as far back as 16 ft from the top of the original cut. The tension cracks indicate material movement and slumping. The sludge wet unit weights (Appendix B, Unit Weights) shown in Figure 23 are averages determined from undisturbed material samples. The process of consolidation increased the unit weights.

Figure 24 is a cross section of the top sludge layer. Shown in the figure is a trial failure surface, 1, and five slices for computing the stability as previously described in Section III. Stability is analyzed as follows:

a. Fill in a table of necessary values (discussed in Section III).

	Values from the Cross Section					Computed Values			
Slice No.	tan α	ΔX ft	P psf	S_U psf	φ deg	B_o	A'_o	N_a	A_o
1	1.73	2.4	260	--	30	1079.5	360.3	$0.25 + \frac{0.25}{F}$	$\frac{360.3}{0.25 + \frac{0.25}{F}}$
2	1.00	3.8	635.2	768.1	0	2413.8	2918.8	1.0	2918.8
3	1.00	2.5	658.0	983.2	0	1645.0	2458.0	1.0	2458.0
4	1.00	1.0	540.1	1339.6	0	540.1	1339.6	1.0	1339.6
5	1.00	1.0	279.5	1339.6	0	279.5	1339.6	1.0	1339.6

(1) The average vertical total stress P acting on the base of each slice is:

$P_{\text{slice 1}} = 130 \text{ pcf} \times 2 \text{ ft} = 260 \text{ psf}$

$P_{\text{slice 2}} = (130 \times 3) + (100 \times 1) + (72.6 \times 2) = 635.2 \text{ psf}$

$P_{\text{slice 3}} = (130 \times 1.5) + (100 \times 1) + (72.6 \times 5) = 658.0 \text{ psf}$

$P_{\text{slice 4}} = (100 \times 0.5) + (72.6 \times 6.75) = 540.1 \text{ psf}$

$P_{\text{slice 5}} = 72.6 \times 7.7 \times 0.5 = 279.5 \text{ psf}$

(2) Average undrained sludge shear strength at the base of each slice is:

$$S_U = S_{U_{\text{vane}}} \text{ (Appendix B, Vane Shear Test)} \times \mu$$

From Figure 16, $\mu = 0.6$. From Figure 22, obtain average $S_{U_{vane}}$ for each slice with a sludge base. Vane shear tests conducted after the slope was cut gave undisturbed values closer to the remolded ones shown in Figure 22. Therefore, $S_{U_{vane}}$ values should probably be the remolded ones. Unloading from cutting the slope apparently reduced the shear strengths. (S_U remolded values were used in the table above.)

(3) Calculate for each slice

$$B_o = P \times \tan \alpha \times \Delta X$$

(4) Calculate for each slice

$$\text{For sludge } A'_o = S_U \times \Delta X$$

$$\text{For sand and surcharge } A'_o = P \times \tan \phi \times \Delta X$$

(5) $N_a = 1.0$ for the sludge bases. For the surcharge base

$$N_a = \cos^2 \alpha + \frac{\cos^2 \alpha \tan \alpha \tan \phi}{F}$$

$$N_a = 0.25 + \frac{0.25}{F}$$

(6) Calculate $A_o = A'_o/N_a$

b. Calculate the factor of safety, $F = \sum A_o/\sum B_o$, by either successive approximations or direct solution.

$$\sum A_o = 8056.0 + \frac{360.3}{0.25 + \frac{0.25}{F}}$$

$$\sum B_o = 5957.9$$

$$F = \frac{8056.0 + \frac{360.3}{0.25 + \frac{0.25}{F}}}{5957.9}$$

By direct solution:

$$F = \frac{8056.0}{5957.9} + \frac{360.3}{5957.9\left(0.25 + \frac{0.25}{F}\right)}$$

$$F = 1.352 + \frac{360.3}{1489.5 + \frac{1489.5}{F}}$$

$$(F - 1.352)(1489.5F + 1489.5) = 360.3F$$

$$1489.5F^2 + 1489.5F - 2013.8 = 0$$

$$F^2 - 0.5939F - 1.352 = 0$$

$$F^2 - 0.5939F + 0.0882 = 1.4402$$

$$(F - 0.2970)(F - 0.2970) = 1.4402$$

$$(F - 0.2970)^2 = 1.4402$$

$$F - 0.2970 = 1.20$$

$$F = 1.49$$

Another trial failure surface, 2, is shown in Figure 24. Stability analysis for surface 2 is as follows:

a. Fill in table as previously described.

	Values from the Cross Section					Computed Values			
Slice No.	tan α	ΔX ft	P psf	S_U psf	φ deg	B_o	A'_o	N_a	A_o
1	1.73	2.3	260.0	--	30	1034.5	345.3	$0.25 + \frac{0.25}{F}$	$\frac{345.3}{0.25 + \frac{0.25}{F}}$
2	1.00	5.8	700.5	676.0	0	4062.9	3920.9	1.0	3920.9
3	1.00	2.5	795.9	921.9	0	1989.8	2304.8	1.0	2304.8
4	0.33	1.0	665.3	--	30	219.6	384.1	$0.9 + \frac{0.17}{F}$	$\frac{384.1}{0.9 + \frac{0.17}{F}}$
5	0.33	1.0	347.7	--	30	114.7	200.7	$0.9 + \frac{0.17}{F}$	$\frac{200.7}{0.9 + \frac{0.17}{F}}$
6	0.33	1.0	40.0	--	30	13.2	23.1	$0.9 + \frac{0.17}{F}$	$\frac{23.1}{0.9 + \frac{0.17}{F}}$

b. $$\sum A_o = 6225.7 + \frac{345.3}{0.25 + \frac{0.25}{F}} + \frac{607.9}{0.9 + \frac{0.17}{F}}$$

$$\sum B_o = 7434.68$$

c. Factor of safety, F

$$F = \frac{\sum A_o}{\sum B_o}$$

$$= 0.8374 + \frac{345.3}{1858.67 + \frac{1858.67}{F}} + \frac{607.9}{6691.21 + \frac{1263.9}{F}}$$

$$= 1.006$$

Obviously, a less-abrupt slope angle is required for stability. Another slope angle was cut at 53 deg in the field test sludge landfill, and no failure occurred.

SECTION V

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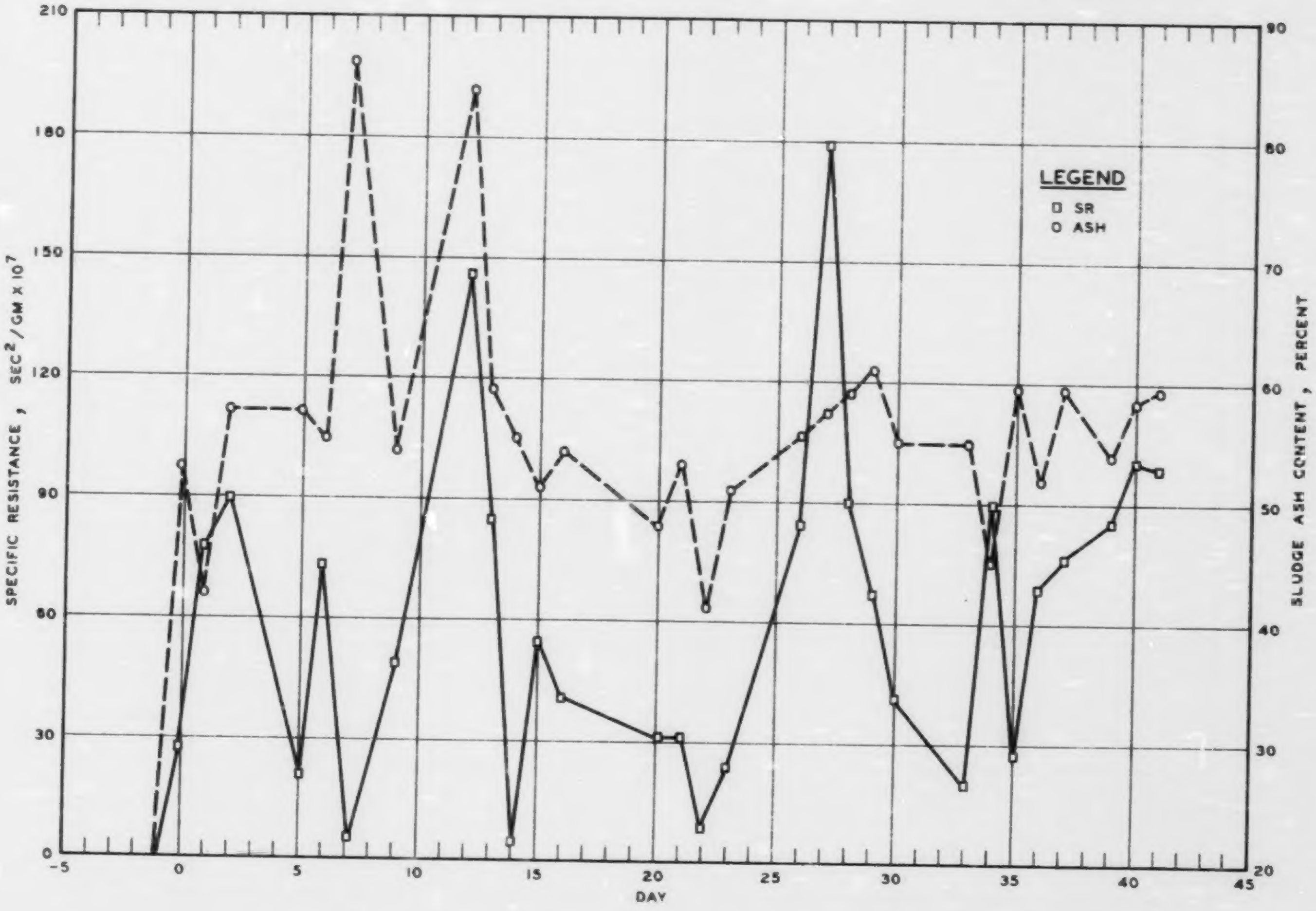


Figure 1. Variability of sludge properties.

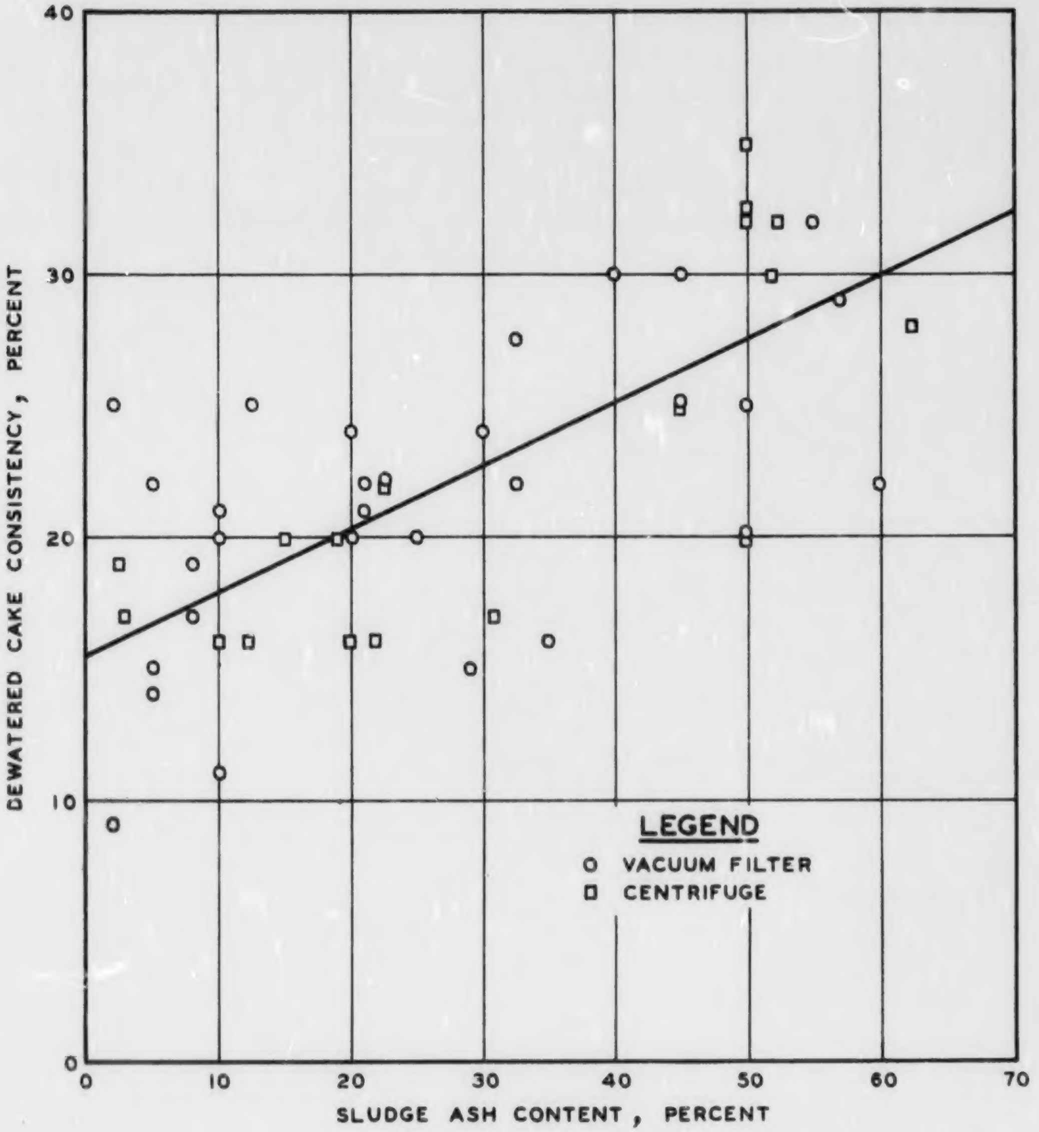


Figure 2. Relationship of sludge dewaterability to ash content.

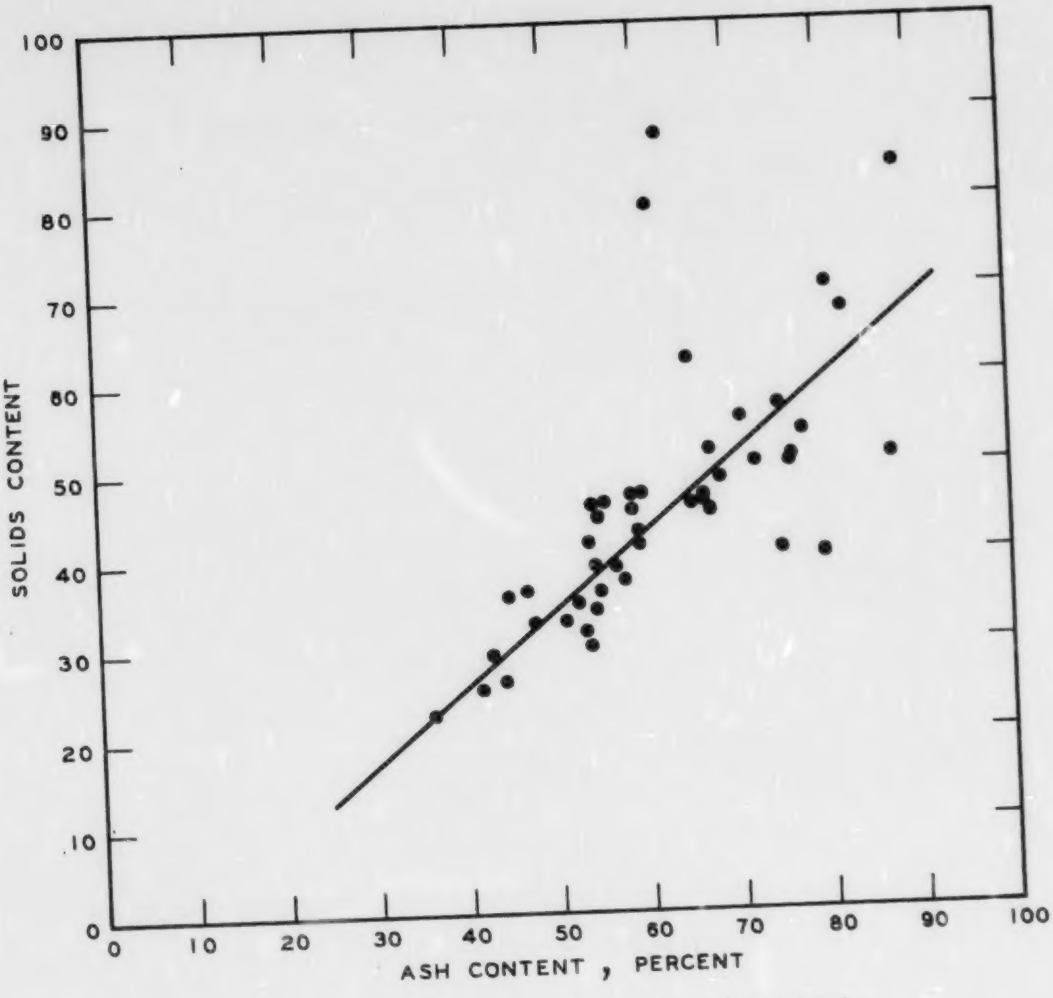


Figure 3. Solids content versus ash content.

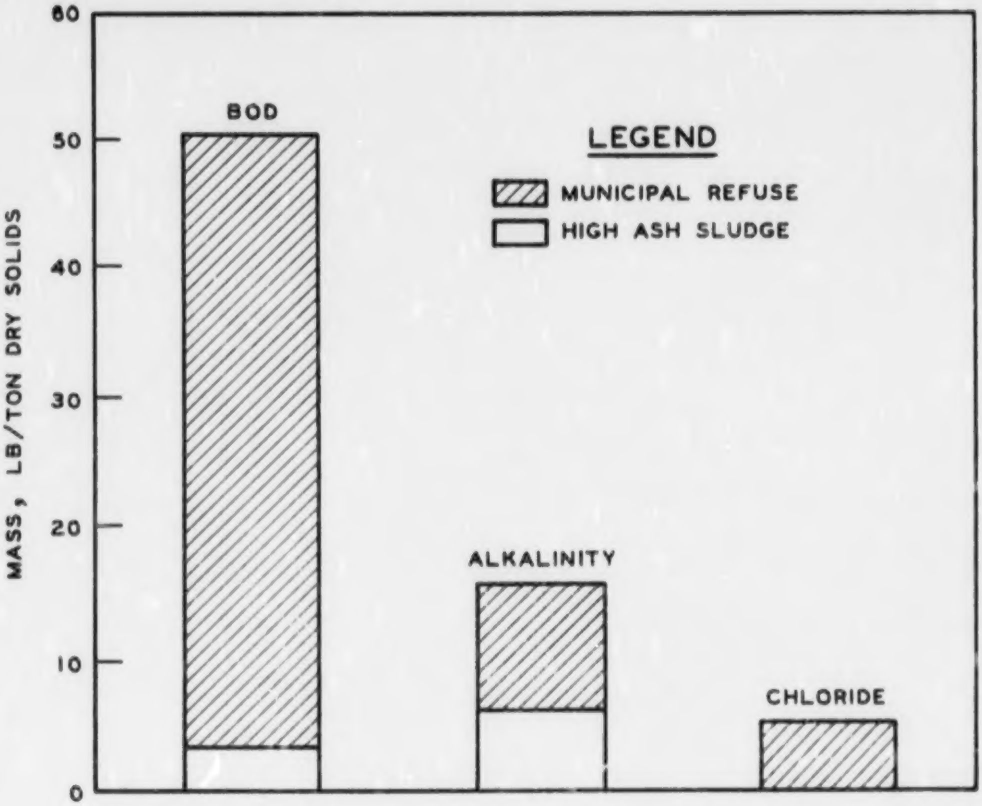


Figure 4. Mass of leachate constituents.

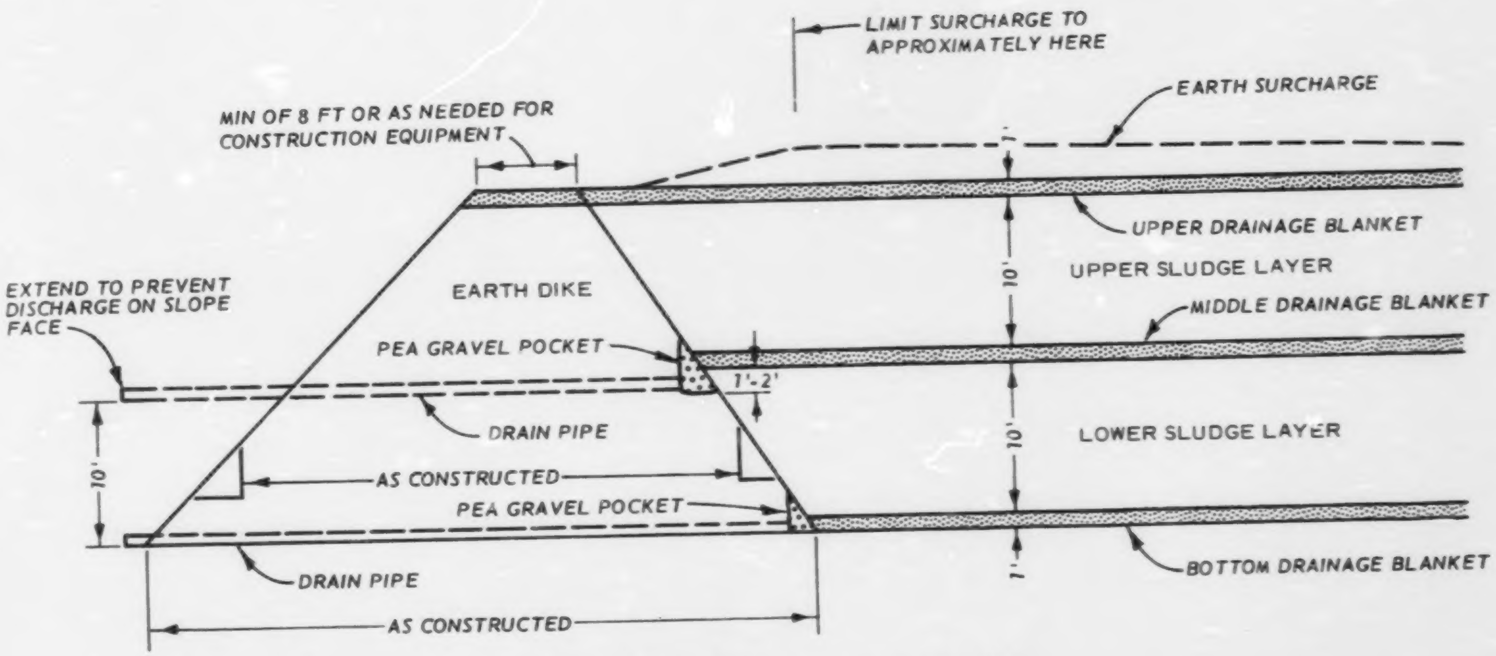
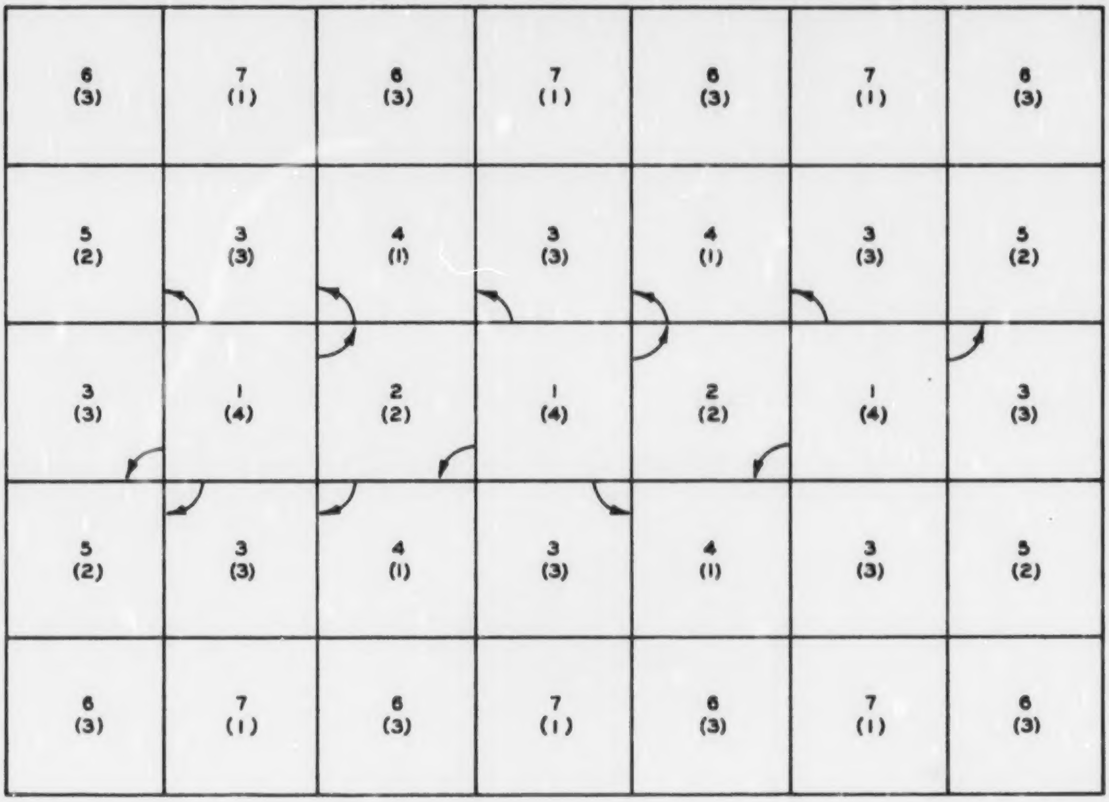

LIMIT SURCHARGE TO APPROXIMATELY HERE
EARTH SURCHARGE
MIN OF 8 FT OR AS NEEDED FOR CONSTRUCTION EQUIPMENT
1'
UPPER DRAINAGE BLANKET
10'
UPPER SLUDGE LAYER
EARTH DIKE
MIDDLE DRAINAGE BLANKET
EXTEND TO PREVENT DISCHARGE ON SLOPE FACE
PEA GRAVEL POCKET
1'-2'
DRAIN PIPE
10'
LOWER SLUDGE LAYER
10'
AS CONSTRUCTED
PEA GRAVEL POCKET
BOTTOM DRAINAGE BLANKET
1'
DRAIN PIPE
AS CONSTRUCTED

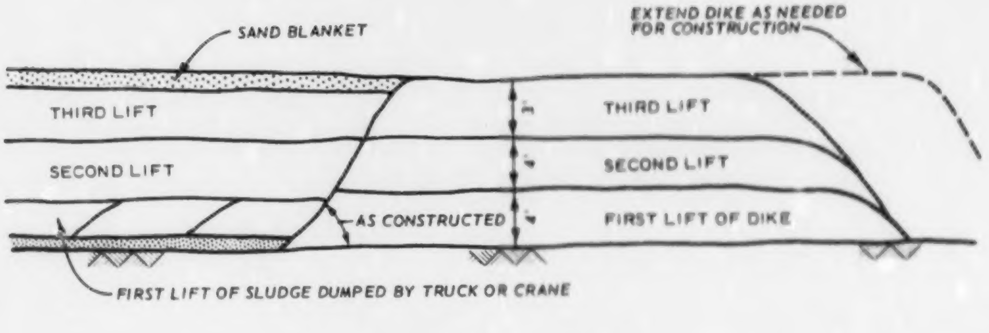
Figure 5. Dike and sludge cross section.


6 (3)
7 (1)
6 (3)
7 (1)
6 (3)
7 (1)
6 (3)
5 (2)
3 (3)
4 (1)
3 (3)
4 (1)
3 (3)
5 (2)
3 (3)
1 (4)
2 (2)
1 (4)
2 (2)
1 (4)
3 (3)
5 (2)
3 (3)
4 (1)
3 (3)
4 (1)
3 (3)
5 (2)
6 (3)
7 (1)
6 (3)
7 (1)
6 (3)
7 (1)
6 (3)

LEGEND

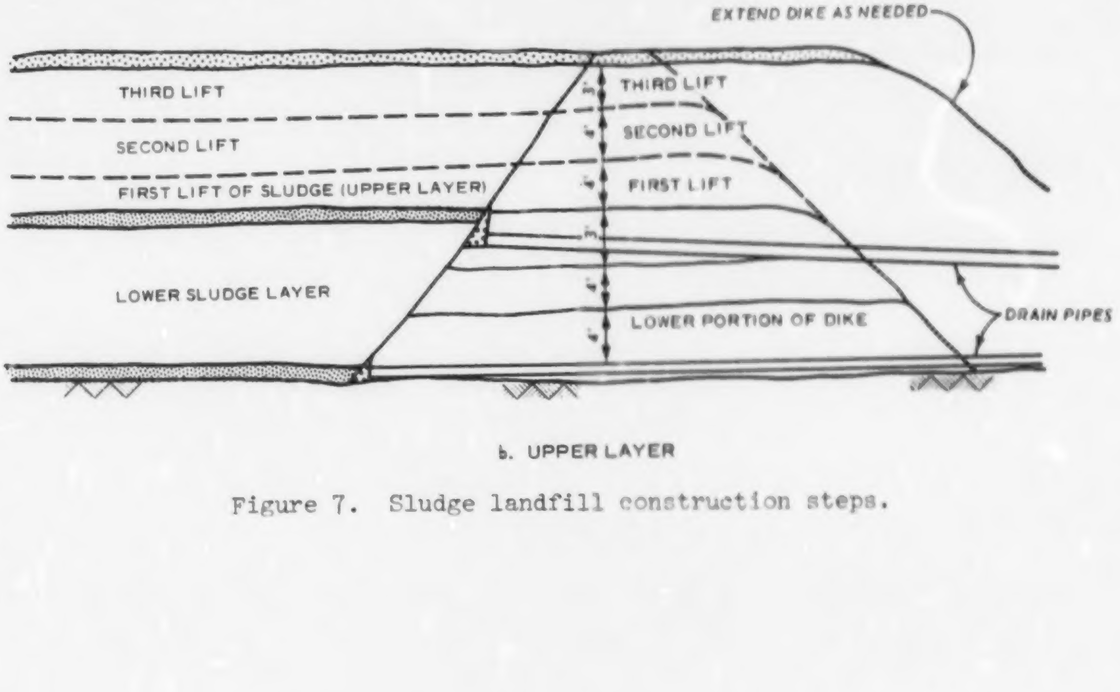
1. NUMBERS 1,2,3, ETC. REPRESENT CONSTRUCTION SEQUENCE.
2. NUMBERS IN PARENTHESES (1), (2), (3), (4), REPRESENT THE NUMBER OF EARTH DIKE SIDES REQUIRED.
3. ↶ = POSSIBLE USE OF MATERIAL IF DIKES REMOVED.

Figure 6. Plan for landfill.


SAND BLANKET
EXTEND DIKE AS NEEDED FOR CONSTRUCTION
THIRD LIFT
SECOND LIFT
THIRD LIFT
SECOND LIFT
AS CONSTRUCTED
FIRST LIFT OF DIKE
FIRST LIFT OF SLUDGE DUMPED BY TRUCK OR CRANE

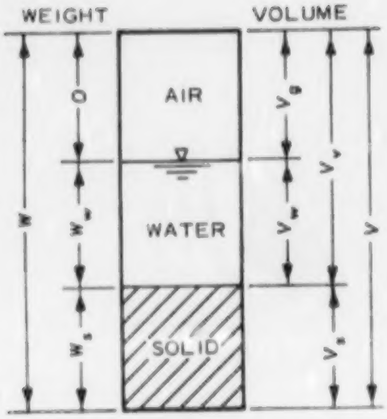
a. LOWER LAYER

NOTE: FIRST, SECOND, AND THIRD LIFTS
OF SLUDGE PLACED BY TRUCK
AND CRANE, DUMPING FROM DIKE


EXTEND DIKE AS NEEDED
THIRD LIFT
THIRD LIFT
SECOND LIFT
SECOND LIFT
FIRST LIFT OF SLUDGE (UPPER LAYER)
FIRST LIFT
LOWER SLUDGE LAYER
LOWER PORTION OF DIKE
DRAIN PIPES

b. UPPER LAYER

Figure 7. Sludge landfill construction steps.



Wet density (wet unit weight) $\gamma_m = \frac{W}{V}$

Dry density (dry unit weight) $\gamma_d = \frac{W_s}{V}$ or

$$\gamma_d = \frac{\gamma_m}{1 + w}$$

Unit weight of water $\gamma_w = \frac{W_w}{V_w} = 62.4 \text{ lb/ft}^3$

Submerged or buoyed unit weight (effective weight of sludge mass below water table) $\gamma' = \frac{W}{V} - \gamma_w$ or $\gamma_m - 62.4$

Water content $w = \frac{W_w}{W_s}$

Specific gravity $G_s = \frac{W_s}{V_s \gamma_w}$

Volume of solids $V_s = \frac{W_s}{G_s \gamma_w}$

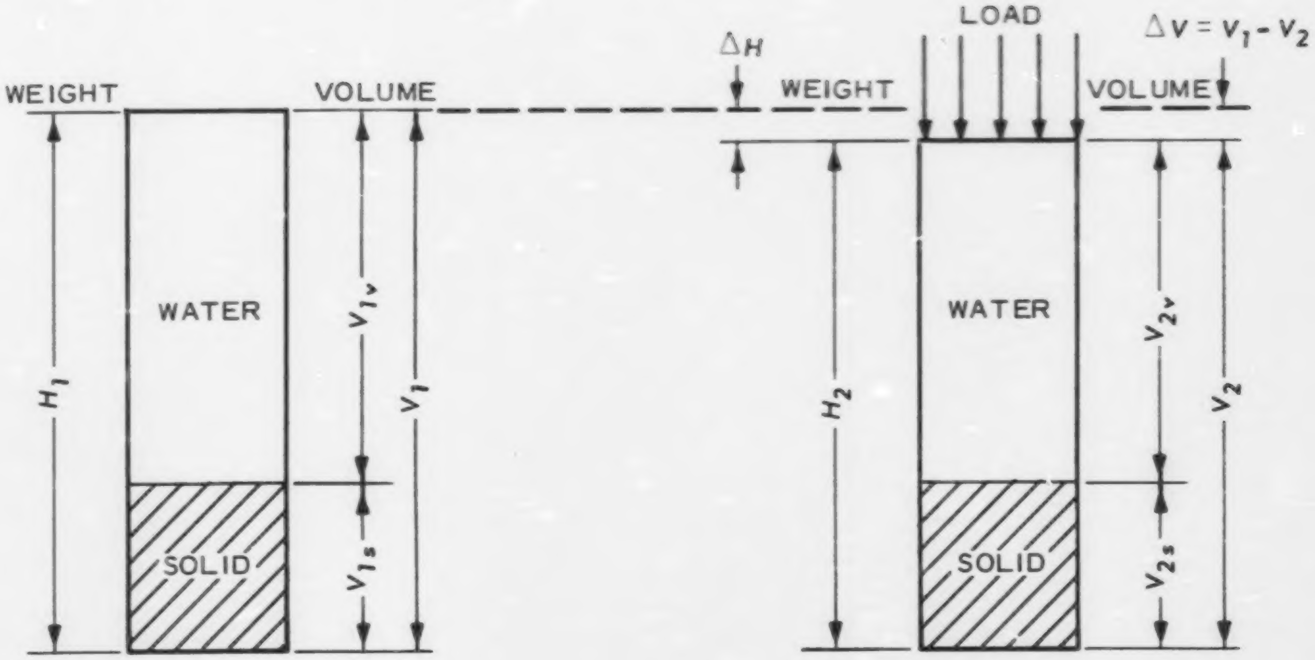
Volume of voids $V_v = V - V_s$

Void ratio $e = \frac{V_v}{V_s}$

Porosity $n = \frac{V_v}{V}$

Degree of saturation $S = \frac{V_w}{V_v}$; $S = \frac{w G_s}{e}$; $S = \frac{w}{\frac{\gamma_w}{\gamma_d} - \frac{1}{G_s}}$

Figure 8. Weight and volume relationships.


WEIGHT
VOLUME
WATER
SOLID
H_1
V_{1v}
V_{1s}
V_1
ΔH
LOAD
$\Delta V = V_1 - V_2$
WEIGHT
VOLUME
WATER
SOLID
H_2
V_{2v}
V_{2s}
V_2

a. INITIAL CONDITION

b. COMPRESSED CONDITION

Figure 9. Compressed sample.

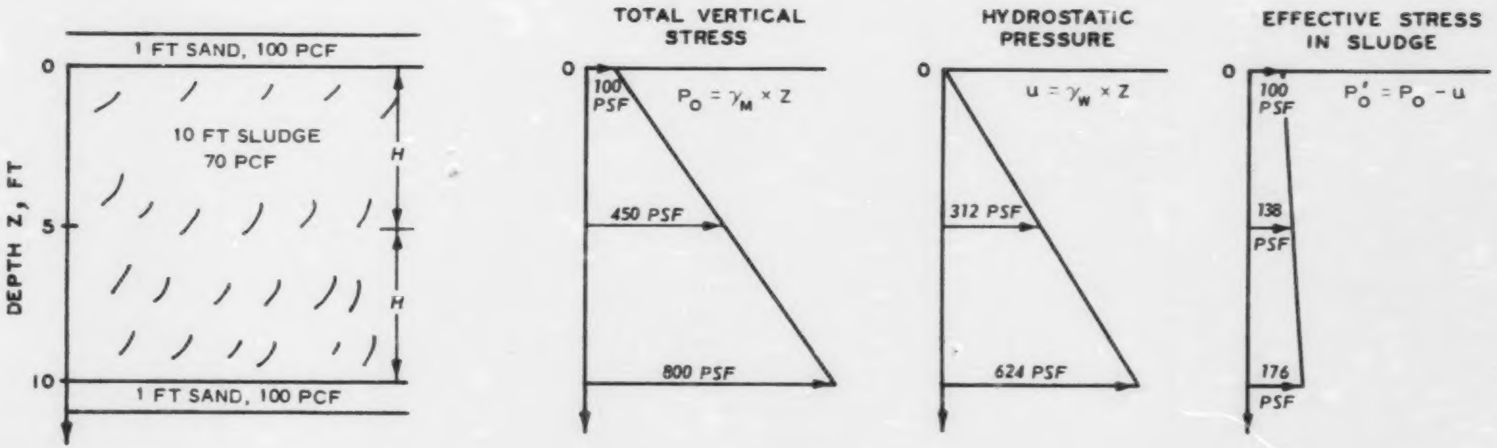

1 FT SAND, 100 PCF
10 FT SLUDGE
70 PCF
1 FT SAND, 100 PCF
DEPTH Z, FT
0
5
10
H
H
TOTAL VERTICAL STRESS
$P_O = \gamma_M \times Z$
100 PSF
450 PSF
800 PSF
HYDROSTATIC PRESSURE
$u = \gamma_W \times Z$
312 PSF
624 PSF
EFFECTIVE STRESS IN SLUDGE
$P_O' = P_O - u$
100 PSF
138 PSF
176 PSF

Figure 10. Load-depth diagram.

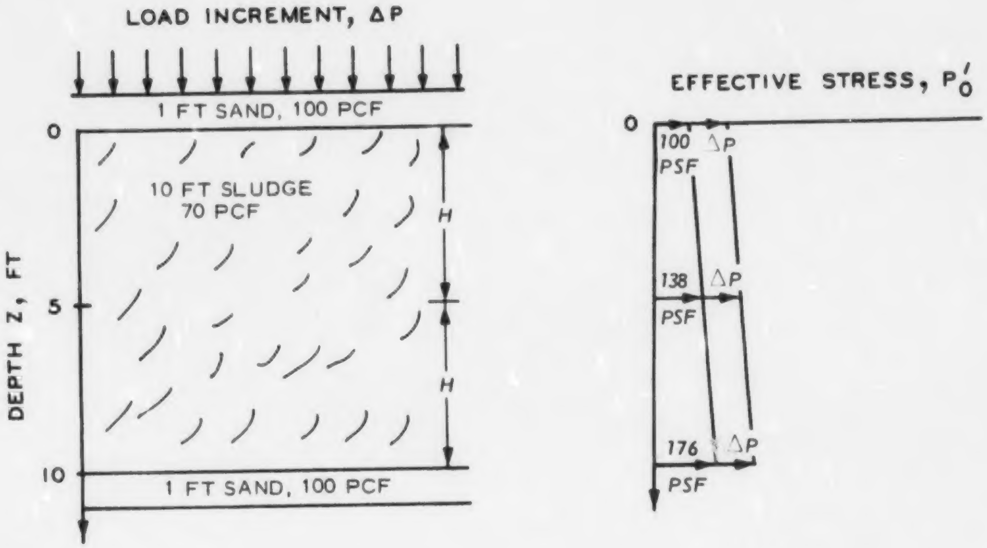

LOAD INCREMENT, ΔP
1 FT SAND, 100 PCF
10 FT SLUDGE 70 PCF
1 FT SAND, 100 PCF
DEPTH Z, FT
0
5
10
H
H
EFFECTIVE STRESS, P'0
0
100 PSF
ΔP
138 PSF
ΔP
176 PSF
ΔP

Figure 11. Load increment added to a sludge layer.

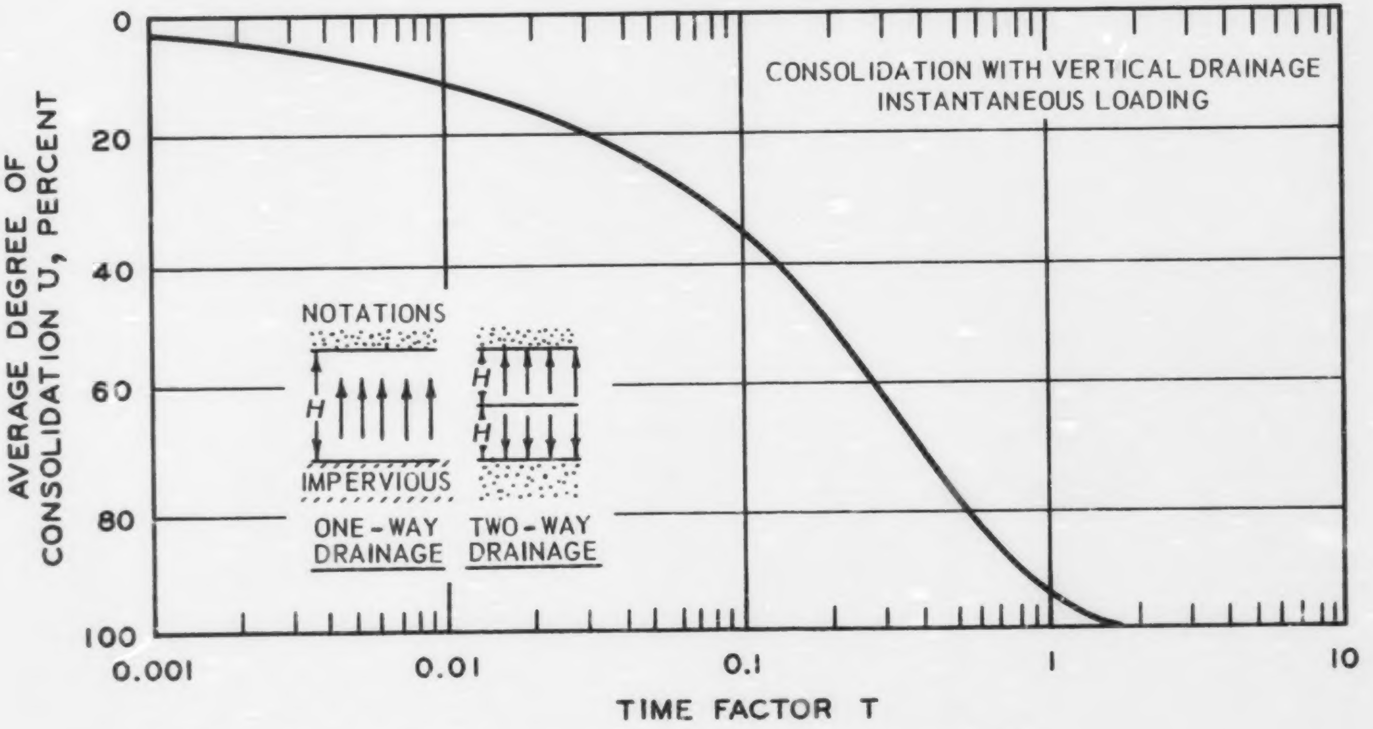
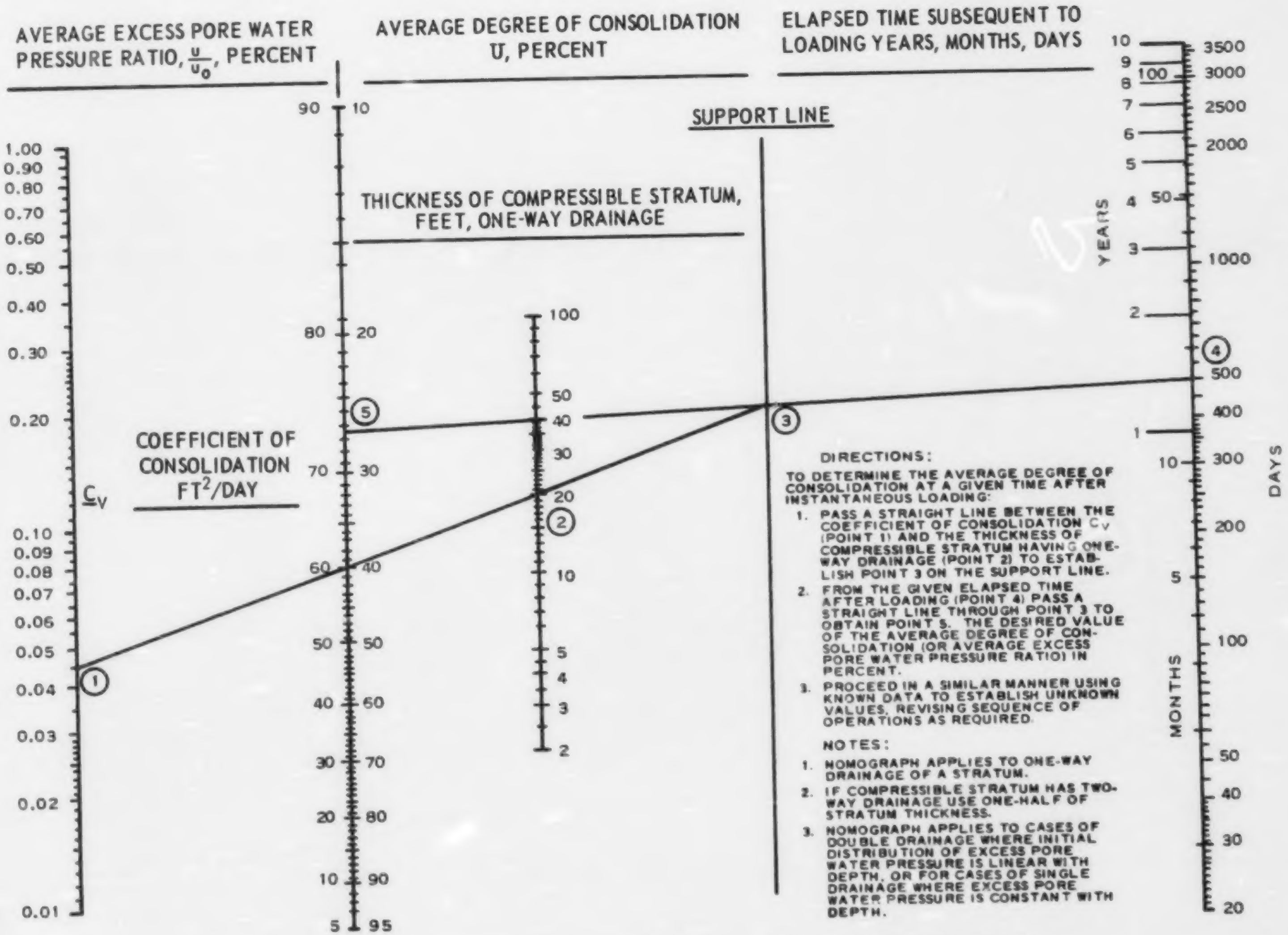


Figure 12. Time factors for consolidation analysis.



DIRECTIONS:

TO DETERMINE THE AVERAGE DEGREE OF CONSOLIDATION AT A GIVEN TIME AFTER INSTANTANEOUS LOADING:

1. PASS A STRAIGHT LINE BETWEEN THE COEFFICIENT OF CONSOLIDATION C_V (POINT 1) AND THE THICKNESS OF COMPRESSIBLE STRATUM HAVING ONE-WAY DRAINAGE (POINT 2) TO ESTABLISH POINT 3 ON THE SUPPORT LINE.
2. FROM THE GIVEN ELAPSED TIME AFTER LOADING (POINT 4) PASS A STRAIGHT LINE THROUGH POINT 3 TO OBTAIN POINT 5. THE DESIRED VALUE OF THE AVERAGE DEGREE OF CONSOLIDATION (OR AVERAGE EXCESS PORE WATER PRESSURE RATIO) IN PERCENT.
3. PROCEED IN A SIMILAR MANNER USING KNOWN DATA TO ESTABLISH UNKNOWN VALUES, REVISING SEQUENCE OF OPERATIONS AS REQUIRED.

NOTES:

1. NOMOGRAPH APPLIES TO ONE-WAY DRAINAGE OF A STRATUM.
2. IF COMPRESSIBLE STRATUM HAS TWO-WAY DRAINAGE USE ONE-HALF OF STRATUM THICKNESS.
3. NOMOGRAPH APPLIES TO CASES OF DOUBLE DRAINAGE WHERE INITIAL DISTRIBUTION OF EXCESS PORE WATER PRESSURE IS LINEAR WITH DEPTH, OR FOR CASES OF SINGLE DRAINAGE WHERE EXCESS PORE WATER PRESSURE IS CONSTANT WITH DEPTH.

Figure 13. Nomograph for consolidation with vertical drainage.

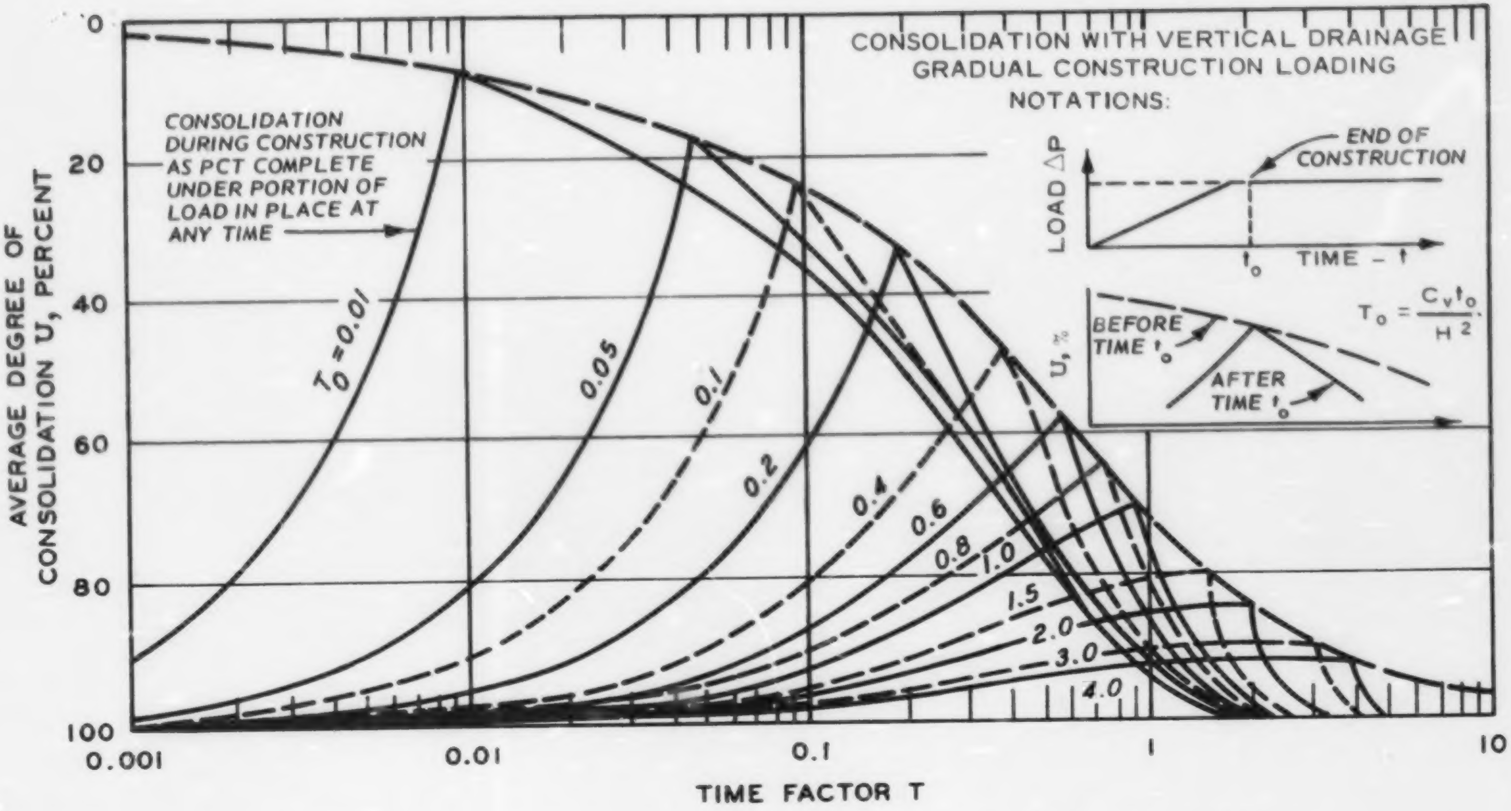


Figure 14. Time factors for consolidation analysis with gradual load application.

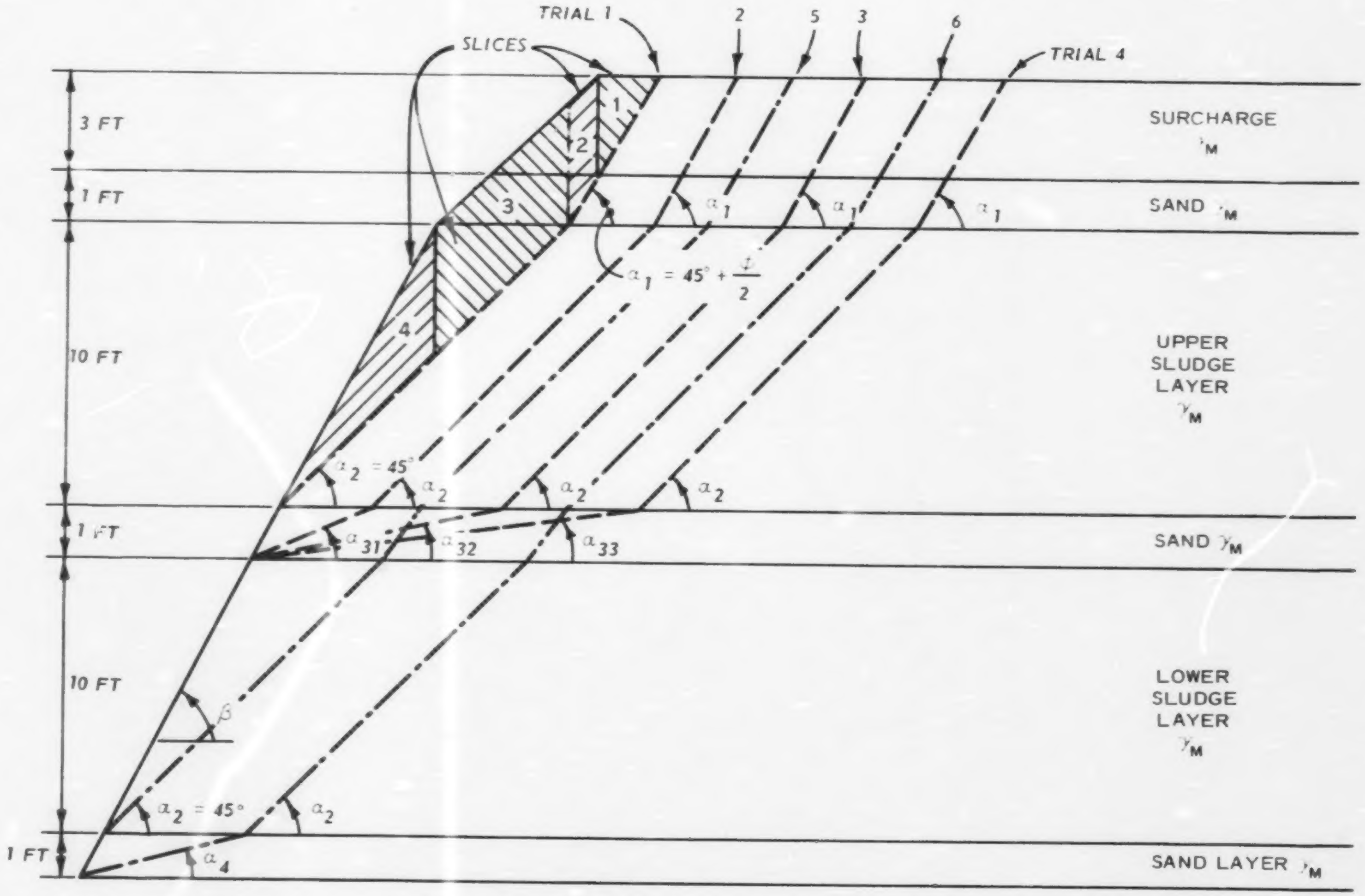
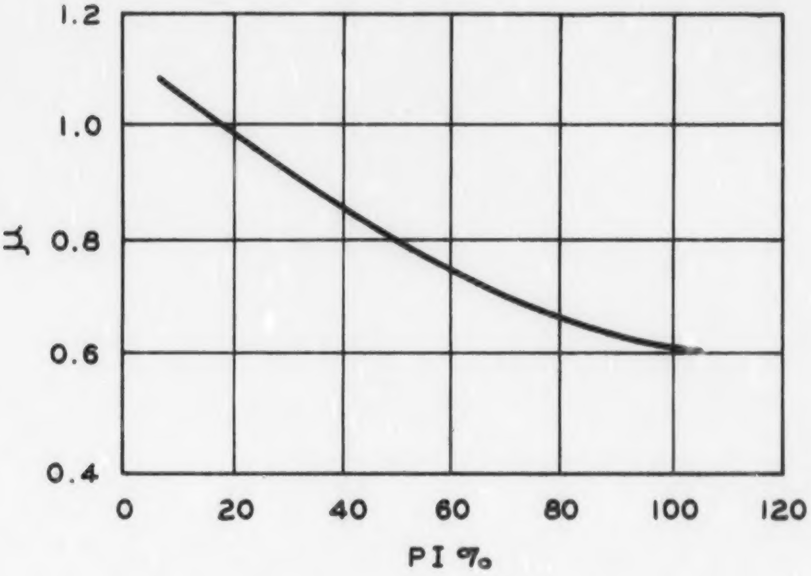

TRIAL 1
SLICES
2
5
3
6
TRIAL 4
1
2
3
4
3 FT
1 FT
10 FT
1 FT
10 FT
1 FT
SURCHARGE γ_M
SAND γ_M
UPPER SLUDGE LAYER γ_M
SAND γ_M
LOWER SLUDGE LAYER γ_M
SAND LAYER γ_M
α_1
α_1
α_1
$\alpha_1 = 45° + \frac{\phi}{2}$
$\alpha_2 = 45°$
α_2
α_2
α_2
α_{31}
α_{32}
α_{33}
β
$\alpha_2 = 45°$
α_2
α_4

Figure 15. Slope analysis.



$$(s_U)_{FIELD} = (s_U)_{VANE} \cdot \mu$$

Figure 16. Correction factor for converting vane shear strengths to field shear strengths (22).

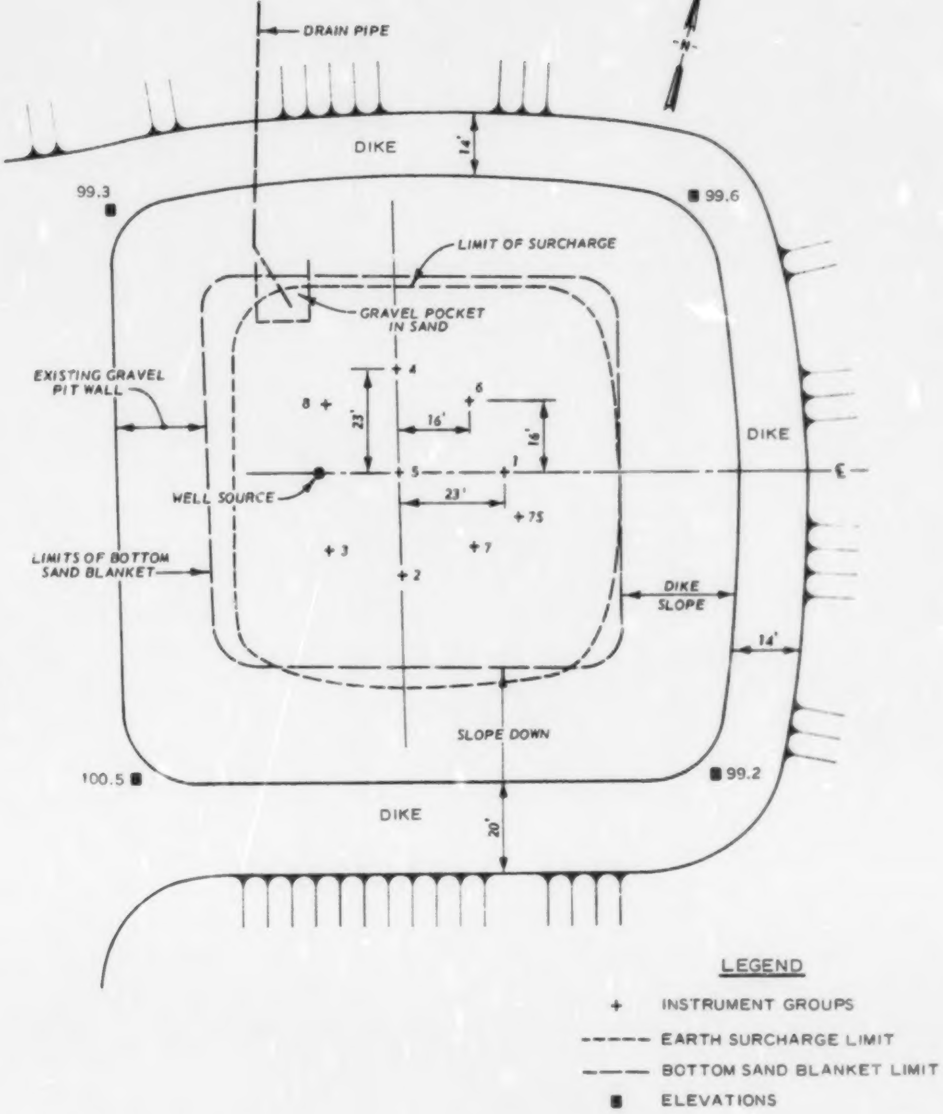
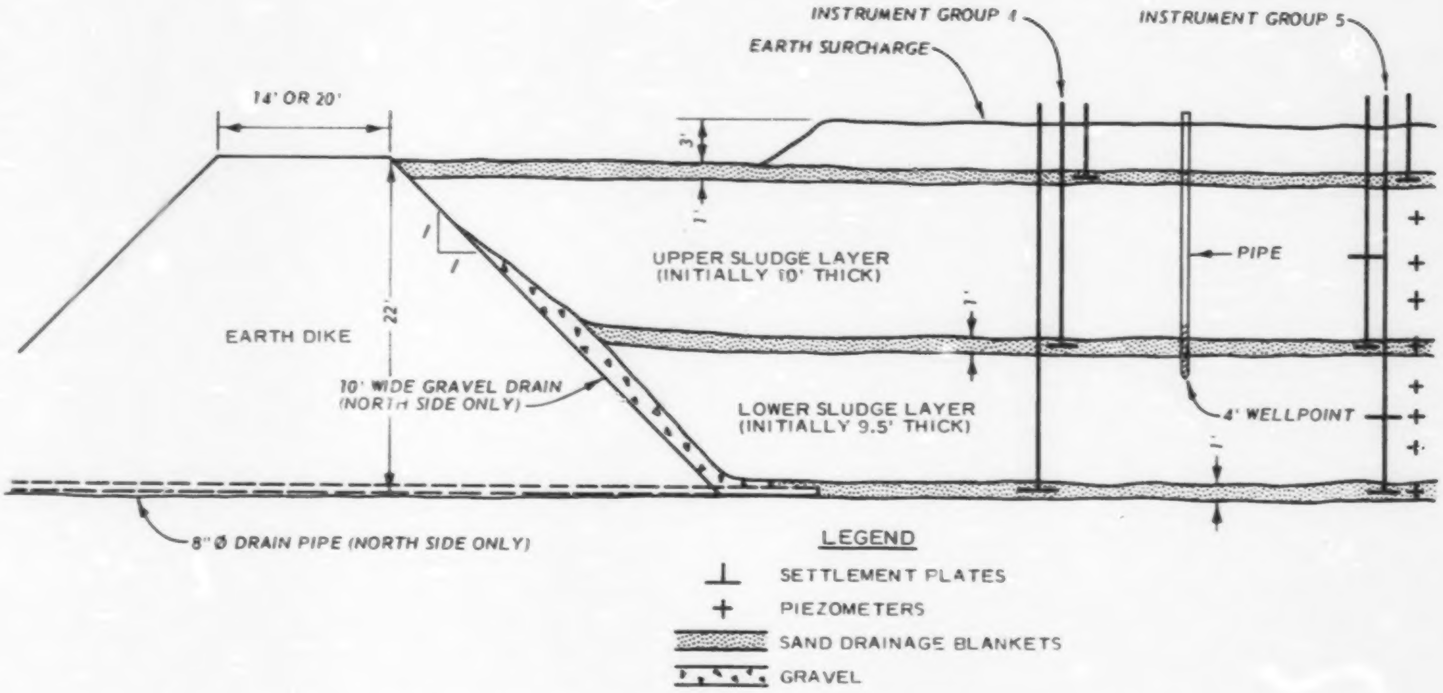

DRAIN PIPE
N
DIKE
14'
99.3
99.6
LIMIT OF SURCHARGE
GRAVEL POCKET IN SAND
EXISTING GRAVEL PIT WALL
4
8
6
23'
16'
16'
DIKE
5
1
℄
WELL SOURCE
23'
7S
3
7
2
LIMITS OF BOTTOM SAND BLANKET
DIKE SLOPE
14'
SLOPE DOWN
100.5
99.2
DIKE
20'
LEGEND
+ INSTRUMENT GROUPS
EARTH SURCHARGE LIMIT
BOTTOM SAND BLANKET LIMIT
ELEVATIONS

Figure 17. Experimental landfill, plan view.



INSTRUMENT GROUP 4
INSTRUMENT GROUP 5
EARTH SURCHARGE
14' OR 20'
3'
1'
1
1
UPPER SLUDGE LAYER (INITIALLY 10' THICK)
PIPE
22'
EARTH DIKE
1'
10' WIDE GRAVEL DRAIN (NORTH SIDE ONLY)
LOWER SLUDGE LAYER (INITIALLY 9.5' THICK)
4' WELLPOINT
1'
8" Ø DRAIN PIPE (NORTH SIDE ONLY)
LEGEND
⊥ SETTLEMENT PLATES
+ PIEZOMETERS
SAND DRAINAGE BLANKETS
GRAVEL

Figure 18. Typical cross section of experimental landfill.

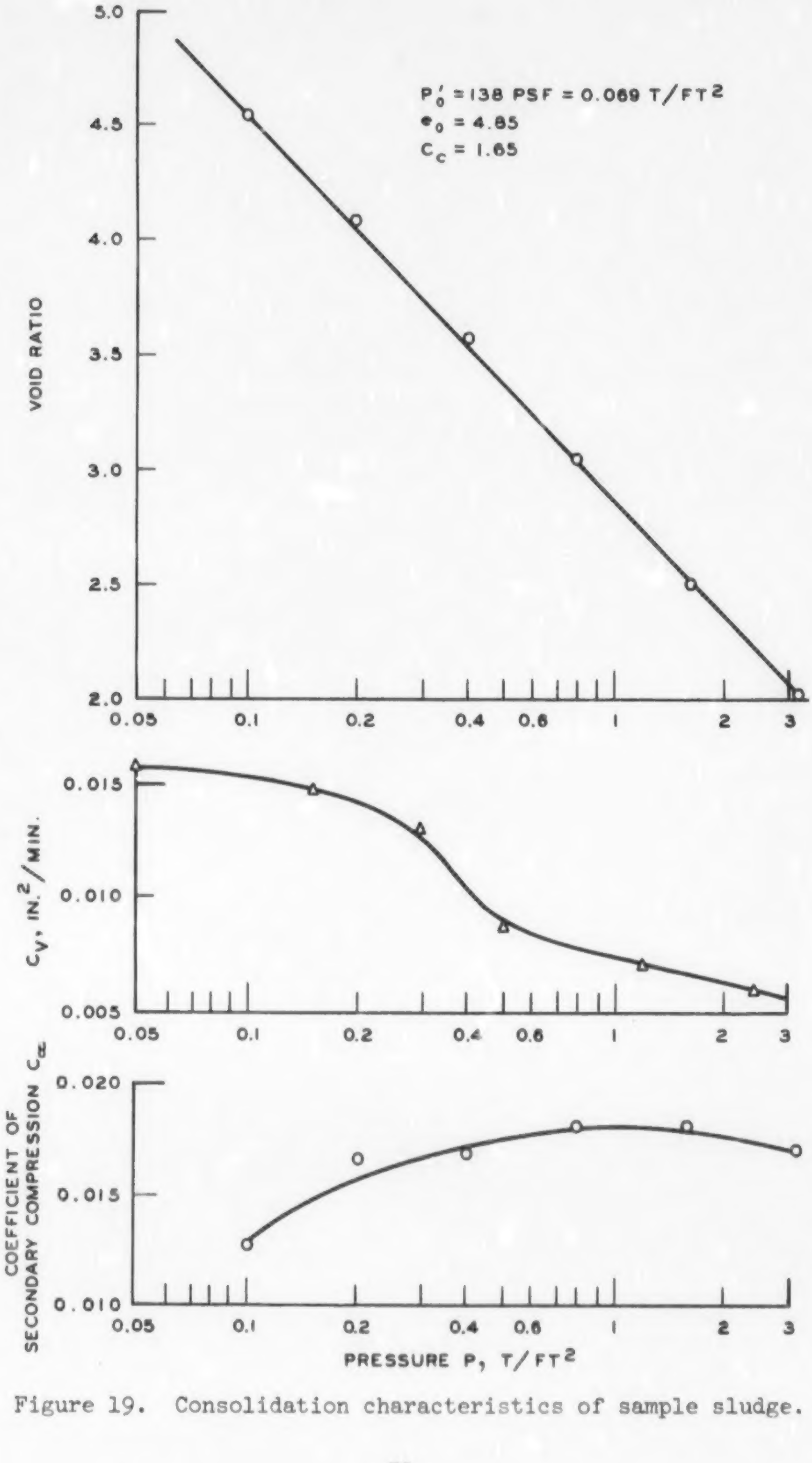


Figure 19. Consolidation characteristics of sample sludge.

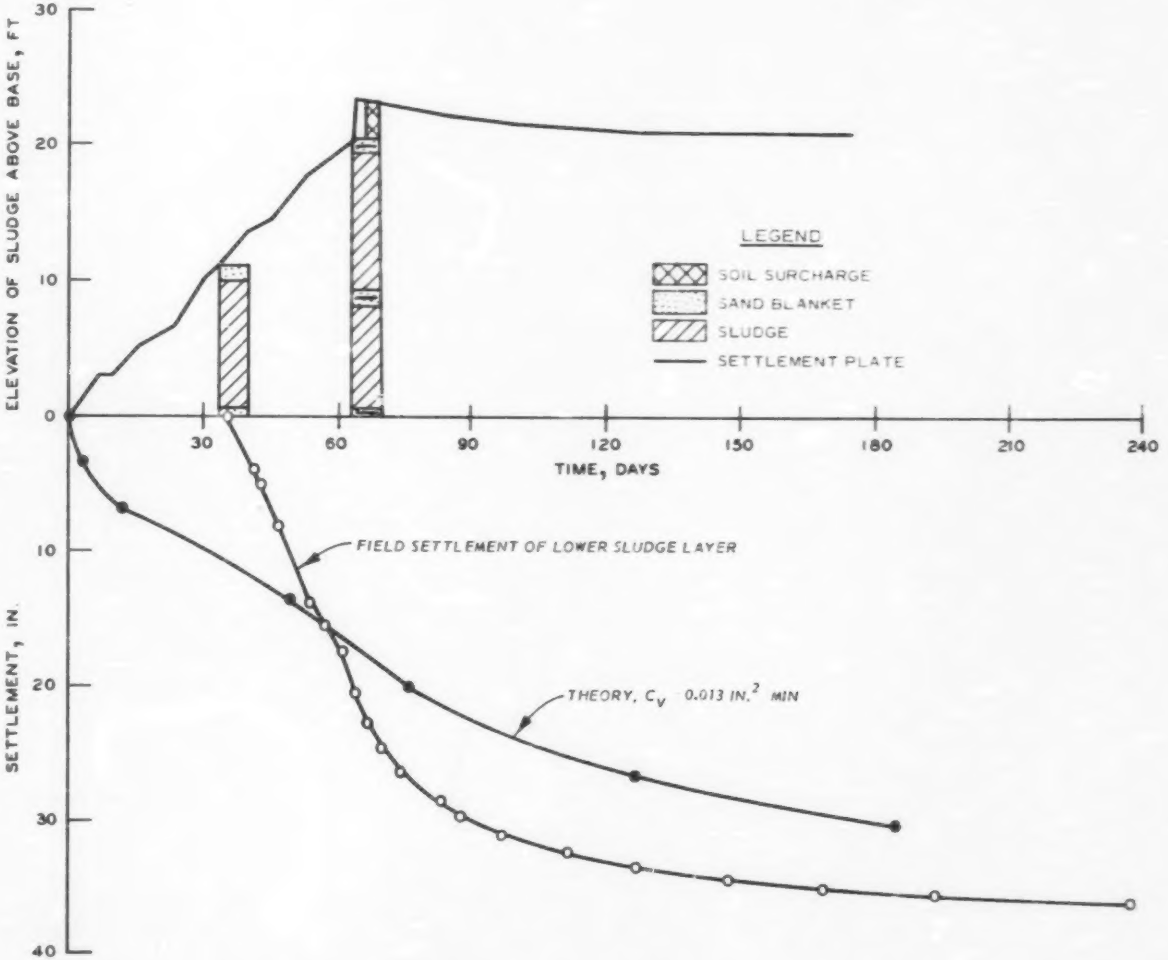


Figure 20. Comparison of predicted and measured time-settlement curves, lower sludge layer.

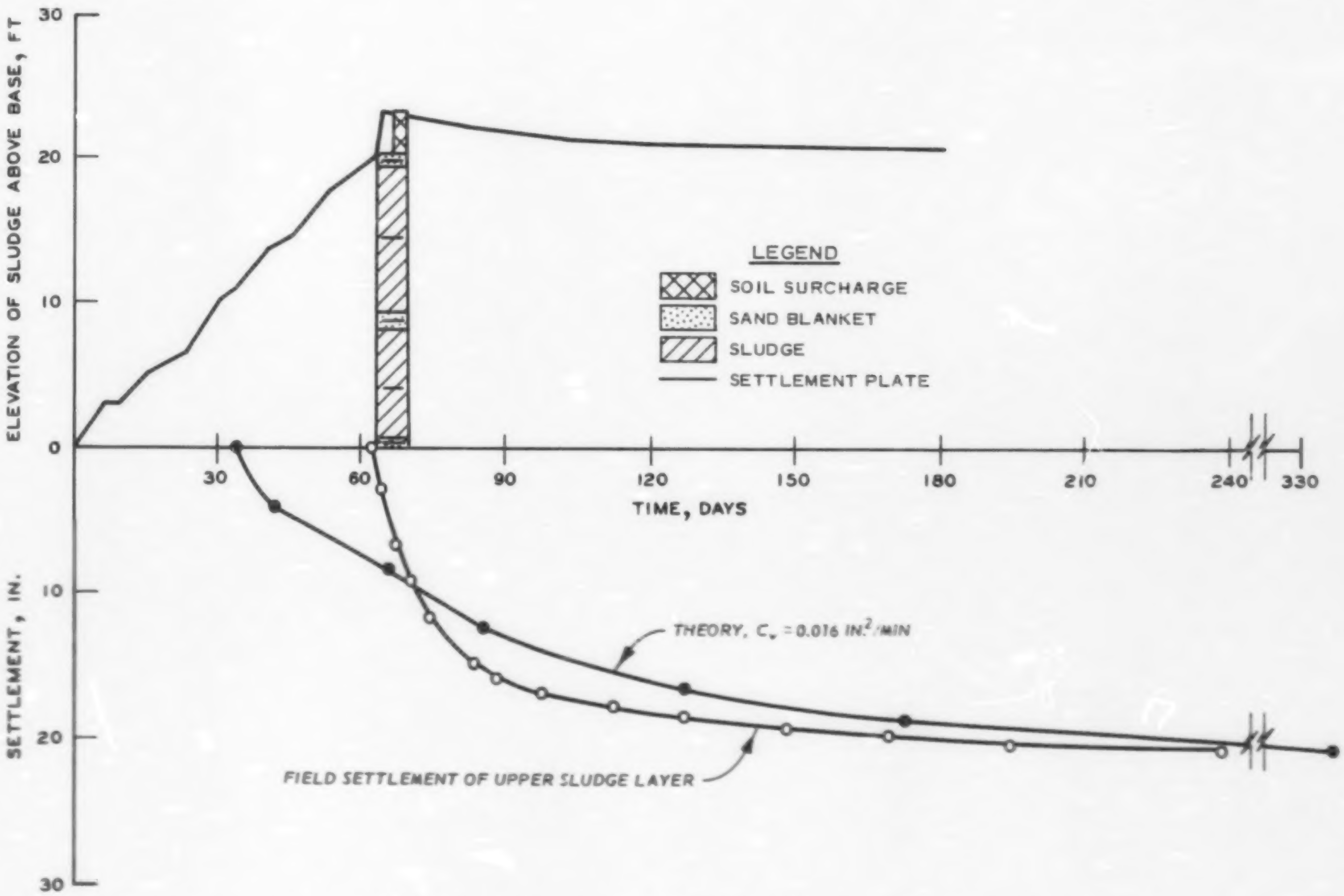
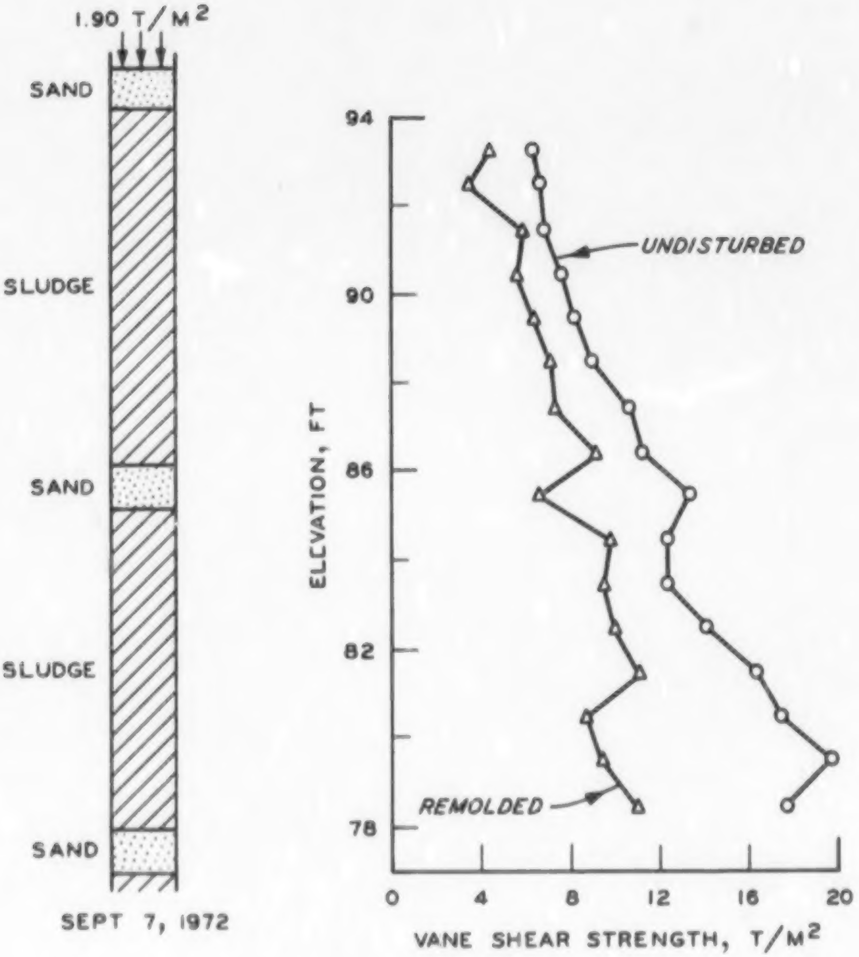


Figure 21. Comparison of actual and predicted time-settlement curves, upper sludge layer.



NOTE: 204.857 × T/M² = P/FT²

Figure 22. Experimental landfill vane shear strength immediately before slope excavation.

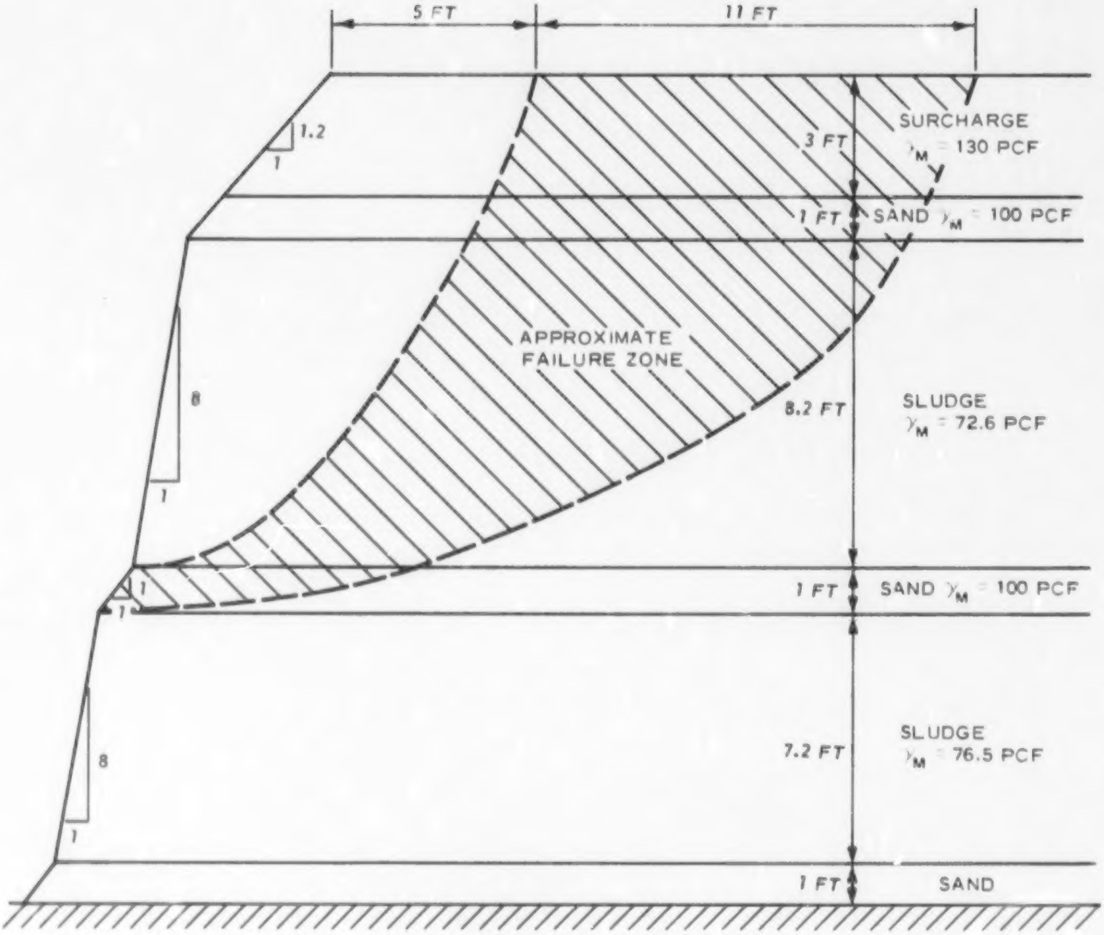

5 FT
11 FT
1.2
1
3 FT
SURCHARGE
γ_M = 130 PCF
1 FT
SAND γ_M = 100 PCF
APPROXIMATE FAILURE ZONE
8
1
8.2 FT
SLUDGE
γ_M = 72.6 PCF
1
1
1 FT
SAND γ_M = 100 PCF
8
1
7.2 FT
SLUDGE
γ_M = 76.5 PCF
1 FT
SAND

Figure 23. Cut slope in experimental sludge landfill.

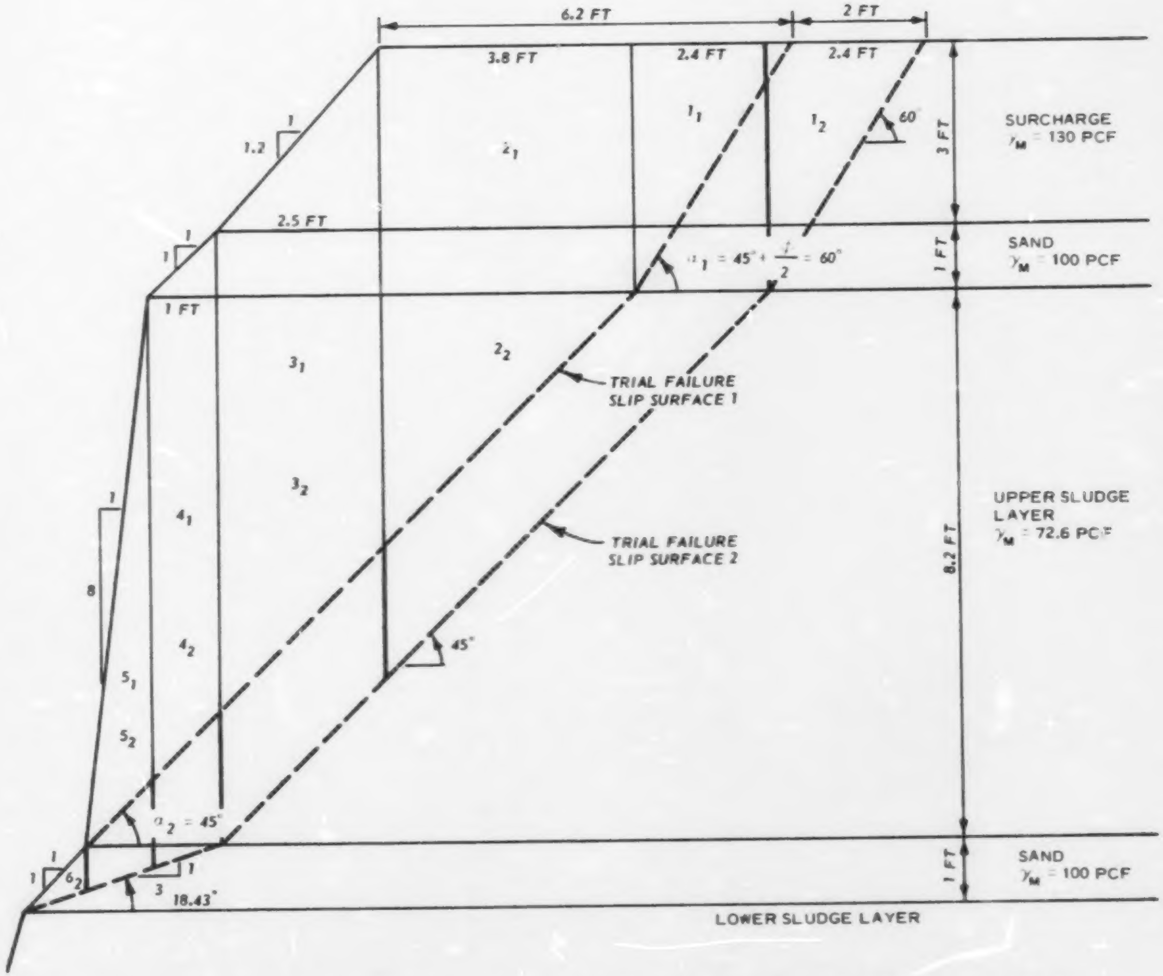

6.2 FT
2 FT
3.8 FT
2.4 FT
2.4 FT
1_1
1_2
2_1
60°
3 FT
SURCHARGE
γ_M = 130 PCF
1
1.2
1
1
2.5 FT
$\alpha_1 = 45° + \frac{\phi}{2} = 60°$
1 FT
SAND
γ_M = 100 PCF
1 FT
3_1
2_2
TRIAL FAILURE
SLIP SURFACE 1
3_2
1
4_1
UPPER SLUDGE
LAYER
γ_M = 72.6 PCF
TRIAL FAILURE
SLIP SURFACE 2
8.2 FT
8
4_2
45°
5_1
5_2
$\alpha_2 = 45°$
1
1
1
6_2
1
3
18.43°
1 FT
SAND
γ_M = 100 PCF
LOWER SLUDGE LAYER

Figure 24. Cross section of top sludge layer for stability analysis.

TABLE 1. PRIMARY SLUDGE PRODUCTION ASSOCIATED WITH PAPER MANUFACTURING

Manufacturing Category	Percentage of Production
Unbleached kraft/linerboard	2
Groundwood/newsprint	3-4
Bleached kraft/market pulp paper, and paperboard	3-4
Bleached and unbleached paperboard	3-4
Nonintegrated fine paper	2-3
Nonintegrated tissue	2-3
Sulfite pulp and paper	3-4
Integrated groundwood and printing paper or specialty paper	3-4
Wastepaper board	0-4
Deinking	10-25

TABLE 2. "NORMAL" SLUDGE COMPOSITION

Type	Consistency Solids, percent	Ash Content percent
Board mills	2-10	50-70
Chemical pulp	1-10	20-50
Deink pulp	3-10	25-60
Groundwood	2-5	1-20
Paper mills	1-5	50-70

TABLE 3. PHYSICAL CHARACTERISTICS OF SLUDGES ORIGINATING IN HIGH ASH SLUDGE LANDFILLS

Mill	>100 Mesh percent		<100 Mesh percent		Ash Content percent	
	Range	Average	Range	Average	Range	Average
A	7-31	21.7	67-99	79.4	41-72	55
B	4-32	11.7	64-94	85.5	42-54	48
C	9-34	17.4	62-90	80.8	54-84	64
D	11-48	23.1	52-87	75.6	35-80	62
E	1-57	30.5	43-70	61.2	66-91	73
F	3-46	16.1	51-97	81.9	54-95	75

TABLE 4. FIBRE CLASSIFICATION FOR SELECTED HIGH ASH SLUDGES

Mill	Fraction Retained on the Indicated Mesh, percent				
	14	28	48	100	<100
1	2.4	1.0	13.7	15.2	67.7
2	3.0	1.7	7.1	11.2	76.9
3	0.2	0.9	3.8	2.3	92.8
4	0.4	2.8	9.7	8.9	78.2

TABLE 5. ANALYSIS OF LEACHATE QUALITY

Sample	I*	II*	III*	IV*	V†
Date sampled	10/19/72	11/21/72	12/12/72	12/29/72	2/10/73
COD (mg/ℓ)	9,580	4,000	4,160	4,700	7,585
BOD (mg/ℓ)	6,614	2,660	2,860	3,250	5,158
pH	7.6	7.7	7.7	7.8	7.5
Specific conductance (μmho/cm)	6,200	3,360	3,100	6,010	4,015
Turbidity (MTU)	56	13	9	17	15
Color (color units)	352	130	165	439	187
Total solids (mg/ℓ)	11,786	4,960	5,130	9,730	8,885
Dissolved solids (mg/ℓ)	11,710	4,840	5,100	9,570	7,651
Suspended solids (mg/ℓ)	76	120	30	160	1,234
Total iron (mg/ℓ)	2.5	1.6	1.5	4.3	3.6
Total hardness (mg/ℓ as $CaCO_3$)	6,810	3,230	3,230	6,565	4,310
Chloride (mg/ℓ)	201	75	70	206	111
Alkalinity (mg/ℓ as $CaCO_3$)	8,670	4,130	4,130	8,770	5,810
Sulfate (mg/ℓ)	<1	<1	<1	<1	<1
Total Kjeldahl nitrogen (mg/ℓ)	--	--	--	--	--
Total phosphorus (mg/ℓ)	--	--	--	--	--

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*Sample extracted from the midsand drainage blanket.

†Sample taken from the bottom slope indicator pipe, which is accountable for the irregular suspended solids concentration.

TABLE 6. TRACE ELEMENTS CONTAINED IN PAPER-MILL PRIMARY SLUDGE

Mill	Elements, lb/ton								
	Cu	Zn	Pb	Hg	Fe	Cd	Cr	Ni	Mg
A	--	4.60	0.04	--	0.80	--	--	--	--
B	*	--	*	--	2.80	--	*	--	*
C	--	--	--	--	4.20	--	--	--	5.00
D	0.19	0.70	*	--	25.50	*	0.03	0.03	0.65
E	--	1.60	0.08	0.09	15.20	--	0.08	0.08	--
F	--	0.12	0.10	0.05	2.60	--	0.04	0.10	--
G	--	0.10	0.20	0.09	13.80	0.02	0.04	0.02	--
H	--	0.20	0.16	0.14	35.00	--	0.08	0.06	--

*Analysis showed presence of only trace amounts.

TABLE 7. LEACHATE ATTENUATION PROPERTIES OF SOILS

Soil Type	Conditions			Removals, percent			
	Hydraulic Loading M gal/acre/day	Aerobic	Anaerobic	COD	Dissolved Solids	Turbidity	Conductivity
Sand	6.8	x	--	93	58	91	57
Organic loam	6.8	x	--	96	77	96	80
Organic loam	6.8	--	x	85	65	68	75
Clay	6.8	x	--	94	76	68	79
Organic loam	27.0	x	--	85	46	51	44

TABLE 8. PHYSICAL PROPERTIES OF PAPER-MILL SLUDGE

Sludge Sample					
No.	Elevation in Layer ft	Consistency Limits	Ash Content percent	Solids Content percent by weight	Specific Gravity
L-0	5	325.4-141.6	35.7	28.5	2.01
L-1*	2.5	257.3-102.7	42.2	27.2	2.05
L-2*	7.5	247.7-105.6	43.3	28.2	2.07
U-1†	2.5	184.5- 86.0	59.4	34.4	2.24
U-2†	4	218.5-101.6	46.5	31.9	2.07
U-3†	5	297.5-133.0	36.5	26.9	1.91
U-4†	7.5	287.4-122.1	34.2	29.0	1.87
U-5†	10	302.8-138.6	32.2	28.4	1.92

*Average of three samples.

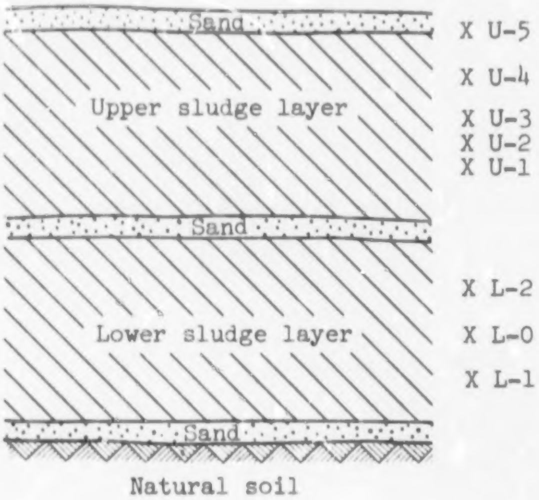
†Average of three tests per sample location.

Sludge unit weight as placed, $\gamma_m \approx 70$ pcf.

Soil surcharge unit weight, $\gamma_m \approx 130.4$ pcf.

Laboratory test sample locations.

Laboratory test sample locations.


Sand
X U-5
X U-4
Upper sludge layer
X U-3
X U-2
X U-1
Sand
X L-2
Lower sludge layer
X L-0
X L-1
Sand
Natural soil

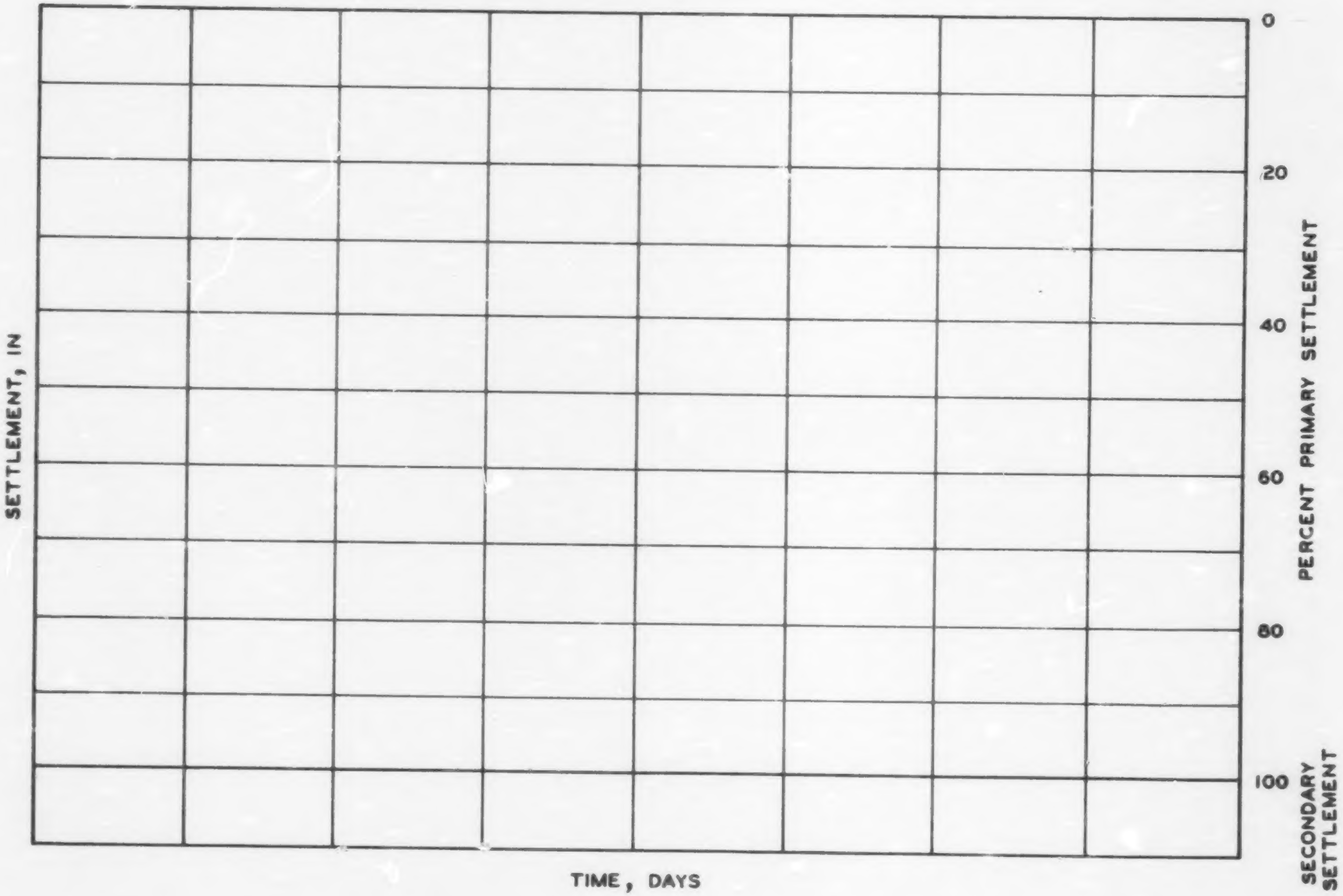


Plate 1. Settlement-time plot.

APPENDIX A

METRIC CONVERSION TABLE

Multiply	By	To Obtain
inches	0.0254	metres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square feet	0.09290304	square metres
acres	4046.856	square metres
gallons (U. S. liquid)	0.003785412	cubic metres
pounds (mass)	0.4535924	kilograms
tons (short)	907.1847	kilograms
pounds (force) per square foot	47.88026	pascals
tons (force) per square foot	95.76052	kilopascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

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*To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

APPENDIX B

TESTING PROCEDURES FOR SLUDGE PROPERTIES

Pulp and paper-mill sludges have the physical appearance of clay interwoven with cellulose fibers. Depending on the manufacturing processes involved, sludge color varies from gray to brown and consistency varies from fluid to plastic. A soft plastic material results from dewatering the sludge. Depending on the method used for dewatering, the solid content ranges from approximately 1 to 65 percent. The manufacturing and conservation processes control the solids composition, which generally includes coating and filler pigments, fibers, and fines. Clay with small amounts of aluminum hydrate, titanium oxide, lime, and iron compose the fixed solids. The remainder of the sludge is cellulose, starch, resins, glue, ink, and organic compounds. High ash sludges have been defined as those which have a fixed solids content of 60 percent or greater (33). As a result of these variations in composition, sludges can show a wide variation in physical properties and behavior.

As for other materials subjected to engineering purposes and analyses, knowledge of some of the physical properties of sludges is desired to characterize their behavior. Knowledge of the physical properties of, experience in, and behavior of the various sludges will lead to better understanding and prediction of their behavior. Based on experience with soil material properties, the following sludge properties are believed to be important:

a. Solids and water contents.

b. Unit weights.

c. Specific gravity of solids.

d. Consistency limits.

e. Permeability.

f. Ash content and organic content.

g. Physical description of the fibers.

If good and accurate records of the above-mentioned properties are kept, eventual accumulation of the information should become very valuable in modifying the test procedures in this manual.

At least three of each of the following tests should be conducted per sludge sample to insure consistency and accuracy of results. Great care should be exercised in obtaining representative sludge samples and in conducting the tests. Sludge samples should be taken and tested every time the manufacturing processes change and probably weekly or biweekly. When samples are taken, they should be stored in airtight containers in a cool place. Airtight containers prevent loss of moisture and may be glass or plastic jars that seal, plastic bags, etc. Metal containers are not recommended because of corrosion. A cool storage atmosphere prevents moisture changes or variation within the sample due to condensation. A refrigerator will provide cool storage.

Test methods for determining sludge properties are given below. References 34-36 describe these methods. All methods except those for ash and organic contents are from Reference 36. The following tests were conducted on essentially one sludge material (9) and were found to be applicable. However, because of the wide variation in sludge properties, test methods may have to be modified on a case-by-case basis. Accumulated records of the various sludge properties and method modifications will form a basis for changing the test methods given below.

SOLIDS AND WATER CONTENTS

Definitions

Solids content, s , is defined as the ratio, expressed as a percentage, of the weight of solids to the weight of the wet sample.

Water content, w , is defined as the ratio, expressed as a percentage, of the weight of water in a sample to the weight of the solids.

Apparatus

The test apparatus should consist of the following:

a. Oven, preferably of the forced-draft type, automatically controlled to maintain a uniform temperature of 85 ± 5°C throughout the oven. (85°C is suggested for organic soils in Reference 25.)

b. Balances, sensitive to 0.1 g for samples weighing 50 to 500 g and to 1.0 g for samples weighing over 500 g.

c. Specimen containers. Seamless containers with lids are recommended. The containers should be of a metal resistant to corrosion (aluminum is satisfactory) or of glass. They should be as small and light in weight as practicable in relation to the amount of material to be used in the determination. For routine tests, a minimum sample size should contain at least 10 g of solids (25).

Procedure

The test procedure is as follows:

a. Record all identifying information for the specimen, such as project name, sample number, date, manufacturing process, or other pertinent data, on a data sheet (Plate B-1 is a suggested form).

b. Record the number and tare weight of the specimen container.

c. Place the specimen in the container, set the lid securely in position, and immediately determine the weight of the container and wet sludge by weighing on an appropriate balance.

d. Before the specimen is placed in the oven, remove the lid; depending on the type of container, the lid is usually placed under the container in the oven. Then place the specimen and container in the oven heated to 85 ± 5°C. Leave the specimen in the oven until it has dried to a constant weight. The time required for drying will vary depending on the type of sludge, size of specimen, oven type and capacity, and other factors. The influence of these factors generally can be established by good judgment and by experience with the sludges being tested and the equipment available in the laboratory. When in doubt, reweigh the ovendried specimens at periodic intervals to establish the minimum drying time required to attain a constant weight. Depending on specimen size, two or three days may be required for drying. Dry specimens may absorb moisture from wet ones; therefore, any dried specimens must be removed before wet specimens are placed in the oven.

e. After the specimen has dried to constant weight, remove the container from the oven and replace the lid. Allow the specimen to cool until the container can be handled comfortably with bare hands. If the specimen cannot be weighed immediately after cooling it should be placed in a desiccator; if a sample is left in the open air for a considerable length of time it will absorb moisture.

f. After the specimen has cooled, determine its dry weight and record it on the data sheet.

Computations

The following quantities are obtained by direct weighing:

a. Weight of tare plus wet sludge, g

b. Weight of tare plus dry sludge, g

The water content in percent of ovendry weight of the sludge is equal to:

$$\frac{(\text{weight of tare plus wet sludge}) - (\text{weight of tare plus dry sludge})}{(\text{weight of tare plus dry sludge}) - (\text{tare})} \times 100$$

or

$$w = \frac{W_w}{W_s} \times 100 \quad \text{or} \quad w = 100 \times \frac{100}{s} - 1$$

where w = water content, percent

W_w = weight of water, g

W_s = weight of dry solids, g

s = percent of dry solids, percent

The solids content in percent of wet weight of the sludge is equal to:

$$\frac{\text{(weight of tare plus dry sludge)} - \text{(tare)}}{\text{(weight of tare plus wet sludge)} - \text{(tare)}} \times 100$$

or

$$s = \frac{W_s}{W} \times 100 \quad \text{or} \quad s = \frac{100}{\frac{w}{100} + 1}$$

where W = total wet specimen weight, g

Possible Errors

Following are possible errors that would cause inaccurate determinations of solids and water contents:

a. Specimen not representative. The specimen must be representative of the sample as required for determination purposes. For example, to determine average water content of a sludge, the specimen must be large enough to contain representative amounts of all constituents.

b. Specimen too small. As a rule, the larger the specimen, the more accurate the determination because of the larger weights involved.

c. Loss of moisture before weighing wet specimen. Even in a covered container a specimen can lose a significant amount of water unless weighed within a short period.

d. Incorrect temperature of oven. The ovendry weight of many sludges is dependent on the temperature of the oven, so variations in temperature throughout the interior of an oven can cause large variations in the computed solids and water content (34).

e. Specimen removed from oven before obtaining a constant ovendry weight.

f. Gain of moisture before weighing ovendry specimen.

g. Weighing ovendry specimen while still hot. The accuracy of a sensitive balance may be affected by a hot specimen container.

h. Incorrect tare weight. The weights of specimen containers should be checked periodically and should be scratched on the containers to avoid possible errors in reading such weights from lists.

UNIT WEIGHTS

Two methods for determining unit weights are presented in the following paragraphs--displacement and volumetric. The displacement method should be used for the plastic-type sludges that can support themselves in uncontained mounds. The volumetric method should be used for the fluid-type sludges.

Definitions

Wet unit weight, γ_m, or wet density, is the weight (solids plus water) per unit of total volume of sludge. The wet unit weight is usually expressed in pounds per cubic foot.

Dry unit weight, γ_d, or dry density, is the weight of ovendried sludge solids per unit of total volume of sludge, and is usually expressed in pounds per cubic foot.

Volumetric Method

The volumetric method is described below.

Apparatus--
The apparatus should consist of the following:

a. A volumetric container of known volume and as large as possible in relation to the constituents of the sludge being tested. The container should be of materials not susceptible to corrosion such as seamless aluminum or glass with lids.

b. The same type of oven and balance as those for solids and water content determinations.

Procedure--
The procedure is as follows.

a. Record on a data sheet (Plate B-2 is a suggested form) all identifying information for the sludge sample.

b. Determine and record the volumetric container weight in grams.

c. Fill the volumetric container with the fluid-type sludge and strike off the top evenly. Weigh the container plus wet sludge and record the weight.

d. Place the sludge and container in the oven and dry it as described for the solids and water content determinations. Obtain and record the weight of the container plus dry sludge.

Computations--
The following quantities are obtained in the test.

a. Weight of tare (volumetric container) plus wet sludge. The tare weight is subtracted from this value to obtain the weight of wet sludge, W .

b. Weight of tare plus dry sludge. The tare weight is subtracted from this value to obtain the weight of dry sludge, W_s , or an alternate procedure is dry weight of specimen computed by the following equation:

$$W_s = \frac{\text{wet weight of specimen}}{1 + \frac{\text{water content of specimen}}{100}} = \frac{W}{1 + 0.01w}$$

c. The inside volume of the volumetric container. Volume V of the wet sludge specimen is equal to this volume.

d. Wet unit weight, γ_m , and dry unit weight, γ_d , expressed in terms of pounds per cubic foot, are computed by the following equations:

$$\gamma_m = \frac{\text{weight in g of wet specimen}}{\text{volume in cc of wet specimen}} \times 62.4 = \frac{W}{V} \times 62.4$$

$$\gamma_d = \frac{\text{weight in g of dry specimen}}{\text{volume in cc of wet specimen}} \times 62.4 = \frac{W_s}{V} \times 62.4$$

Displacement Method

Apparatus--

The apparatus should consist of the following:

a. Wire basket of sufficient size to contain the sludge specimen.

b. Can, or container, of sufficient size to submerge the wire basket and specimen.

c. Specimen container. The container should be of materials not susceptible to corrosion such as seamless aluminum or glass with lids.

d. Paintbrush.

e. Microcrystalline wax or paraffin.*

f. Container for melting wax, preferably with a self-contained thermostat.

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*Among the many microcrystalline waxes found satisfactory are Product 2300 of the Mobile Oil Company, Microwax 75 of the Gulf Oil Corporation, and Wax 1290 of the Sun Oil Company. Paraffin alone is not as suitable for sealing sludge specimens because its brittleness and shrinkage upon cooling will cause cracking, especially in thin sections and at corners; a mixture of 50 percent paraffin and 50 percent petrolatum has properties that approach those of a microcrystalline wax (36).

g. Thermometer, range 0 to 50°C, graduated in 0.1 deg.

h. The same type of oven and balance as those for solids and water content determinations.

i. A hobby tool with a high-speed rotating circular saw (preferably about 3/4-in.-diameter saw blade).

Procedure--

The procedure is as follows:

a. Record on a data sheet (Plate B-3 is a suggested form) all identifying information for the sludge sample.

b. Determine, if not previously established, the specific gravity of the wax to be used. (About 0.9 g per cm^2, but it should be determined for each batch of wax.)

c. Cut a specimen from the sample to be tested. (The size of the specimen is not very important provided the capacity of the balance is not exceeded. In general, more accurate results will be obtained with larger specimens.) Carefully trim the specimen to a fairly regular shape. The circular saw hobby tool is recommended for trimming because of the sludge fibers. Re-entrant angles should be avoided, and any cavities formed by large particles being pulled out should be patched carefully with material from the trimmings.

d. Determine and record the wet weight of the sludge specimen.

e. Cover the specimen with a thin coat of melted wax, either with a paintbrush or by dipping the specimen in a container of melted wax. Apply a second coat of wax after the first coat has hardened. The wax should be sufficiently warm to flow when brushed on the sludge specimen, yet it should not be so hot that it penetrates the pores of the sludge. If hot wax comes in contact with the specimen it may cause the moisture to vaporize and form air bubbles under the wax.

f. Determine and record the weight of the wax-coated specimen in air.

g. Determine and record the submerged weight of the wax-coated specimen. This is done by placing the specimen in a wire basket hooked onto a balance and immersing the basket and specimen in a can of water as shown in Figure B-1. In order to directly measure the submerged weight of the wet sludge and wax, the balance must have been previously balanced with the wire basket completely submerged in the can of water. Insure that the specimen is fully submerged, and that the basket is not touching the sides or bottom of the container. Measure the temperature of the water.

h. Remove the wax from the specimen. It can be peeled off after a break is made in the wax surface. Use the entire sample, or as much as is free of wax inclusions, for a water content determination.

Computations--

The following quantities are obtained directly in the test:

a. Weight of uncoated specimen, W .

b. Weight of sludge plus wax. The weight of uncoated specimen, W , is subtracted from this value to obtain the weight of wax.

c. Weight of sludge plus wax in water.

The following computations will be made:

a. Divide the weight of the wax by its specific gravity. This gives the volume of the wax.

b. Subtract the weight of the wax-coated specimen in water from its weight in air. The difference divided by the density of water at the test temperature (see Table B-1) is numerically equal to the volume of the coated specimen in cubic centimeters.

c. Subtract the volume of wax from the volume of the coated specimen to obtain the total volume of the sludge specimen, V .

d. Compute the water content of the specimen. If the entire specimen is used for the water content determination, obtain the dry weight of specimen, W_s , directly. If only a portion of the initial specimen is used for the water content determination, compute the dry weight of specimen according to the following equation:

$$W_s = \frac{\text{wet weight of uncoated sludge}}{1 + \frac{\text{water content of wet sludge}}{100}} = \frac{W}{1 + \frac{w}{100}}$$

Based on the information above, compute the unit weights as specified hereinbefore.

Possible Errors

Following are possible errors that would cause inaccurate determinations of the total volume:

Volumetric Method--

a. Imprecise measurement of volumetric cylinder. Three height measurements and nine diameter measurements should be made to determine the average height and diameter of the cylinder. Precise calipers should be used for these measurements rather than flat scales.

b. Imprecise weight measurements.

Displacement Method--

Voids on surface of specimen not filled by wax or air bubbles formed beneath wax.

SPECIFIC GRAVITY

Definition

The specific gravity of solids, G_s , of a sludge is the ratio of the weight in air of a given volume of solids at a stated temperature to the weight in air of an equal volume of distilled water at a stated temperature.

Apparatus

The apparatus should consist of the following:

a. Volumetric flask, 500-cm^3 capacity or larger.

b. Vacuum pump, with piping and tubing for connections to each flask (as shown in Figure B-2). The connection to each flask should be provided with a trap to catch any water drawn from the flask.

c. Thermometer, range 0 to 50°C, graduated in 0.1 deg.

d. Evaporating dish.

e. Water bath.

f. The same type of oven and balance as those for solids and water content determinations.

Calibration of Volumetric Flask

The volumetric flask will be calibrated for the weight of the flask and water at various temperatures. The flask and water are calibrated by direct weighing at the range of temperatures likely to be encountered in the laboratory. The calibration procedure is as follows:

a. Fill the flask with deaired-distilled (or deaired-demineralized) water to slightly below the calibration mark and place in a water bath which is at a temperature between 30 and 35°C. Allow the flask to remain in the bath until the water in the flask reaches the temperature of the water bath. This may take several hours. Remove the flask from the water bath, and adjust the water level in the flask so that the bottom of the meniscus is even with the calibration mark on the neck of the flask. Thoroughly dry the outside of the flask and remove any water adhering to the inside of the neck above the graduation; then weigh the flask and water to the nearest 0.01 g. Immediately after weighing, shake the flask gently and determine the temperature of the water to the nearest 0.1°C by immersing a thermometer to the middepth of the flask.

b. Repeat the procedure outlined in step a at approximately the same temperature. Then make two more determinations, one at room temperature and the other at approximately 5 deg less than room temperature.

c. Draw a calibration curve showing the relation between temperature and corresponding weights of the flask plus water. Prepare a calibration curve for each flask used for specific gravity determinations and maintain the curves as a permanent record. A typical calibration curve (omitting the fine grid necessary for accurate determinations) is shown in Figure B-3.

Preparation of Sample

Particular care should be taken to obtain representative samples for determination of specific gravity of solids. The sample of sludge should be at its natural water content, because sludges with high organic content would be difficult to rewet after having been oven-dried.

Procedure

The procedure for determining the specific gravity of sludges at natural water content is as follows.

a. Record all identifying information for the sample, such as project name, sample number, and other pertinent data, on a data sheet (see Plate B-4 for suggested form).

b. Place a representative sample of sludge equivalent to approximately 50 to 80 g (or greater depending on the size of sludge constituents) ovendry weight in a dish and, by means of a spatula, mix with sufficient distilled or demineralized water to form a slurry, if it is not already a slurry. Place the slurry in a volumetric flask and fill the flask approximately half full with distilled water.

c. Connect the flask to the vacuum line as shown in Figure B-2 and apply a vacuum of approximately 29.0 in. of mercury. Agitate the flask gently at intervals during the evacuation process; commercially available mechanical agitators may be used for this purpose. The length of time that vacuum should be applied will depend on the type of sludge being tested. The process probably will require 6 to 8 hr; some sludges may require less time for removal of air but this should be verified by experimentation. To insure continuous boiling, the temperature of the flask and contents may be elevated somewhat above room temperature by immersing in a water bath at approximately 35°C. Additionally, entrapped air* should be removed by boiling** the suspension gently for at least 30 min while occasionally rolling the flask to assist in the removal of air. The boiling process should be observed closely as loss of material may occur. Allow flask and contents to cool, preferably overnight, before filling and checking.

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*Air removal from organic sludges usually cannot be accomplished by the application of vacuum. Therefore, it will be necessary to boil the suspension contained in the flask for about 30 min, adding distilled or demineralized water carefully from time to time to prevent boiling the sample dry. The flask should at all times be approximately half full.

**Use of indirect heat such as a sand bath is recommended.

d. Fill the flask with deaired distilled water to about 3/4 in. below the graduation and apply a vacuum slightly less than that which will cause vigorous boiling (as vigorous boiling may result in a loss of solids). To determine if the suspension is deaired, slowly release the vacuum and observe the lowering of the water surface in the neck of the flask. If the water surface is lowered less than 1/8 in., the suspension can be considered sufficiently deaired.

e. Fill the flask until the bottom of the meniscus is coincident with the calibration line on the neck of the flask. Thoroughly dry the outside of the flask and remove the moisture on the inside of the neck by wiping with a paper towel. Weigh the flask and contents to the nearest 0.01 g. Immediately after weighing, stir the suspension to assure uniform temperature, and determine the temperature of the suspension to the nearest 0.1°C by immersing a thermometer to the middepth of the flask.

f. Carefully transfer the contents of the flask to an evaporating dish. Rinse the flask with distilled water to insure removal of all of the sample from the flask. Oven-dry the sample to a constant weight at a temperature of 85 ± 5°C. Allow the sludge to cool to room temperature in a desiccator and determine the weight of the sludge to the nearest 0.01 g.

g. Record all weights on the data sheet.

Computations

The following quantities are obtained by direct weighing:

a. Weight of flask + water + solids at test temperature = W_{bws} in grams.

b. Weight of tare plus dry sludge in grams. The tare weight is subtracted from this value to obtain the weight of dry sludge, W_s . The specific gravity of solids is computed to two decimal places by the equation:

$$G_s = \frac{W_s K}{W_s + W_{bw} - W_{bws}}$$

where K = correction factor based on the density of water at 20°C (see Table B-1). Unless otherwise required, specific gravity values reported shall be based on water at 20°C.

W_{bw} = weight of flask plus water at test temperature in grams (obtained from calibration curve as shown in Figure B-3).

Possible Errors

Following are possible errors that would cause inaccurate determinations of specific gravity:

a. Imprecise weighing of flask and contents. Since the computation of the specific gravity of solids is based on a difference in weights which is small in comparison with the weights themselves, the same balance should be used for calibrating the volumetric flask and for determining the specific gravity whenever the calibration curve is used.

b. Temperature of flask and contents not uniform. Both in calibrating the flask and determining the specific gravity, utmost care should be taken to insure that measured temperatures are representative of the flask and contents during the times when the weighings are made.

c. Flask not clean. The calibration curve will not remain valid if dirt accumulation changes the weight of the flask. Also, if the inside of the neck is not clean, an irregular meniscus may form.

d. Moisture on outside of flask or inside of neck. When calibrating the flask for a temperature lower than room temperature, there is a tendency for condensation to form on the flask despite careful drying and rapid weighing. Whenever possible, weighing should be done at approximately the same temperature as that of the flask.

e. Meniscus not coincident with mark on neck of flask. One drop of water too much makes an error of approximately 0.05 g. This error can be minimized by taking the average of several readings at the same temperature. When the suspension is opaque, a strong light behind the neck is helpful in seeing the bottom of the meniscus.

f. Use of water containing dissolved solids. It is essential that distilled or demineralized water be used exclusively to insure the continued validity of the flask calibration curve.

g. Incomplete removal of entrapped air from sludge suspension. This is the most serious source of error in the specific gravity determination and will tend to lower the computed specific gravity. The suspension must be thoroughly evacuated or boiled and the absence of entrapped air verified as described in Procedure. (It should be noted that air dissolved in the water will not affect the results, so it is not necessary to apply vacuum to the flask when calibrating or after filling the flask to the calibration mark.)

CONSISTENCY LIMITS

The consistency limits are water contents that define the limits of the various stages for a given sludge. The principal stages from an engineering standpoint are shown in Figure B-4. The liquid limit (LL) and the plastic limit (PL) define the upper and lower limits, respectively, of the plastic range of a sludge; the numerical difference between these two limits expresses the plasticity of a sludge and is termed the plasticity index (PI). The shrinkage limit (SL) defines the lower limit of the semisolid range of a sludge. Detailed procedures for determining the liquid and plastic limits are given below, and a detailed procedure for determining the shrinkage limit is also given. Sludges containing a large percentage of fibres will not easily lend themselves to the consistency tests. When the fibres interfere with the test procedures, this fact should be noted.

Liquid Limit Test

Definition--

The liquid limit of a sludge is the water content, expressed as a percentage of the weight of ovendried sludge, at which two halves of a sludge pat separated by a groove of standard dimensions will close at the bottom of the groove along a distance of 1/2 in. under the impact of 25 blows in a standard liquid limit device.

Apparatus--

The apparatus should consist of the following:

a. Liquid limit device, as shown in Figures B-5 and B-6, having a crank and cam to lift and then drop a brass cup onto a block of resilient material. A motorized liquid limit device may be used, provided that it meets the specifications of the conventional device and that vibration is imperceptible during operation. However, comparative tests should be performed to insure that the motorized device gives the same results as those obtained using the conventional device. Several details in the construction of the liquid limit device are of particular importance. First, the material of the base will be Micarta No. 221A or a hard rubber of equal dynamic resiliency. A 5/16-in.-diameter steel ball bearing dropped from a height of 10 in. above the top of the base will rebound at least 7.3 in. but not more than 9 in. for a base to be satisfactory. The top of the base will be well polished, and rubber feet are necessary to eliminate the influence of the supporting table. The cam will be shaped so that the height of the cup is maintained constant for a short section at the end of the turn rather than rising continuously to the point of release (37). The weight of the cup with the cam follower will be 175 ± 15 g.* Figures B-5 and B-6 show the cup supported by a pin made integral with the cam follower; however, a separate pin may be used to support the cup provided there is assurance that the cup will always be removed from the support for shaping and grooving the soil pat (38).

b. Grooving tool, conforming in general to the dimensions shown in Figure B-5. The critical dimensions of the grooving tool are those which govern the shape and depth of the sludge groove. The gage for checking height of drop of the cup will be 10 ± 0.2 mm (0.394 ± 0.008 in.). The shape of the gage may vary, depending on the manufacturer, but it should have a square edge, not round.

c. Spatula, having a blade about 4 in. long and about 3/4 in. wide.

d. Mixing dish or bowl.

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*Material is not to be added to the cup to meet this requirement.

e. Specimen containers. Seamless metal or glass containers with lids are recommended. The containers should be resistant to corrosion.

f. The same types of balance and oven as those for solids and water content determinations.

Check and Adjustment of Liquid Limit Device--
Periodically, the following points will be checked.

a. The cam will be shaped so that the last 1/8 in. of movement along the cam before the cup drops will cause no change in elevation of the cup.

b. The pin on which the cam follower rests should not be worn sufficiently to permit sideplay.

c. The screws connecting the cup to the cam follower will be tight.

d. A groove should not have been worn in the cup to the extent that it can be felt distinctly by hand. If so, the cup will be replaced.

e. When, at the point of contact between the cup and the base, either a dent in the base or a flat on the cup can be felt distinctly by hand, the worn item will be replaced or repaired. A worn cup can be remedied by moving the cam follower to obtain a new point of impact. A dent in the base can be eliminated by removing a thin layer and repolishing.

f. The grooving tool will be inspected to insure that the dimensions controlling the groove in the sludge are as shown in Figure B-5. The grooving tool will be replaced when the width of the tip exceeds 2.1 mm (0.083 in.) or is less than 1.9 mm (0.075 in.).

g. The height of drop of the cup will be adjusted as follows: By means of the gage on the handle of the grooving tool and the thumbscrew at the rear of the device, adjust the height to which the cup is lifted so that the point on the cup that comes in contact with the base (not the lowest point of the cup) is 10 ± 0.2 mm (0.394 ± 0.008 in.) above the base, as shown in Figure B-5. Secure the adjustment by tightening the thumbscrew on top of the device and then recheck the adjustment. A flashlight is helpful in making this critical adjustment.

Preparation of Material--
Material will be selected and prepared as follows.

a. It is essential that the same carefully prepared sludge mixture be used for determining both the liquid and plastic limits. Sludges of different plasticity will not be mixed. Furthermore, if the natural water content is to be determined, the specimen will be taken from an identical mixture to permit valid correlations. If other test results are to be correlated with the liquid and plastic limits, the material used for the determinations will be the same as that tested.

b. Whenever possible, sludges will be at the natural water content when preparation for testing is begun. If drying has occurred before testing, the limit values may change. The plasticity of sludges containing significant organic content may be highly sensitive to drying. The effects of drying can be determined by comparing the liquid limit values of specimens in "undried," "airdried," and "ovendried" states.

c. Samples will be of sufficient size to produce 150 to 200 g of material. This amount will also provide enough material for performing the plastic limit test. The sample material will be mixed thoroughly with distilled or demineralized water until it has a water content somewhat above the liquid limit (a consistency requiring between 15 and 20 blows to cause closure of the groove); with experience it becomes possible to judge very closely when this condition is reached. The mixture will be covered with an airtight lid and left at least overnight, and preferably for 24 hr, and then remixed thoroughly.

Procedure--

The liquid limit test procedure is as follows:

a. Record all identifying information for the specimen, such as project name and other pertinent data, on a data sheet (Plate B-5 is a suggested form).

b. Place 50 to 80 g of the thoroughly mixed specimen in the brass cup and level it off to a depth of approximately 1 cm. Divide the sludge in the cup with the grooving tool so that a clean, sharp groove is formed, as shown in Figure B-7. When making the groove, hold the cup in the hand with the cam follower upward and draw the grooving tool, beveled edge forward, through the specimen, downward away from the cam follower. The grooving tool should always be held perpendicular to the cup at the point of contact, as shown in Figure B-7. With sludges containing a large amount of organic matter it may not be possible to draw the grooving tool through the specimen without tearing the sides of the groove. In such cases the groove may possibly be made with a sharp spatula, using the grooving tool only for final checking of the groove.

c. Connect the cup to the device and turn the crank at a rate of two revolutions per second. Count the blows until the two halves of the sludge pat come in contact at the bottom of the groove along a distance of 1/2 in. as shown in Figure B-8. Record on the data sheet the number of blows required to close the groove.

d. Remove 5 to 10 g of sludge from the portion of the sludge pat which flowed together, and place it in a specimen container. Determine the water content of the specimen in accordance with the procedures for solids and water content determinations. All weighing will be accurate to 0.01 g, and water contents in percent will be computed to one decimal place.

e. Transfer the sludge remaining in the cup to the mixing dish. Wash and dry the cup and grooving tool and repeat steps b, c, and d for three additional portions of the specimen for which the water content has been adjusted by drying. Drying may be accomplished by continued mixing with a spatula, aided, if desired, by a small electric fan. The water content adjustment for each portion will be sufficient to produce a noticeable variation in the number of blows required to close the groove. The object of this adjustment is to vary the number of blows required to close the groove from below 25 to above 25, though preferably from not less than 15 to not more than 35. It is recommended that the water content of two portions be adjusted to require between 15 and 25 blows and of two others to require between 25 and 35 blows. Material remaining in the mixing dish will be preserved for the plastic limit test.

Computations--

Computations will be made as follows.

a. After all necessary data have been recorded on the data sheet, compute the water content of each specimen as follows:

$$\text{Water content, percent} = \frac{\text{weight of water}}{\text{weight of ovendried sludge}} \times 100$$

b. Determine the liquid limit from a plot of water content versus number of blows on a semilogarithmic graph. Plot water content on an arithmetic scale (ordinate) and plot the corresponding number of blows on a logarithmic scale (abscissa) as shown in Plate B-5. The best straight line (called the "flow line") is drawn through the four plotted points. The liquid limit is the water content corresponding to the intersection of this straight line and the 25-blow line on the graph. Record the liquid limit to the nearest 0.1 percent water content but omit the percent designation. However, the final results may be reported to the nearest whole number.

Plastic Limit Test

Definition--

The plastic limit of a sludge is the water content, expressed as a percentage of the weight of ovendried sludge, at which the sludge begins to crumble when rolled into a thread 1/8 in. in diameter.

Apparatus--

The apparatus will consist of the following:

a. Surface for rolling the thread, such as a fine-ground glass plate or a smooth tabletop of linoleum or dense, fine-grained wood. Clean, white paper may be placed on the surface for rolling provided the type of paper will not result in accumulations of lint in the specimen.

b. Spatula, having a blade about 4 in. long and about 3/4 in. wide.

c. Specimen containers, of the type used for the liquid limit test procedure.

d. Balance and oven of the types used for liquid limit test, sensitive to 0.01 g.

Preparation of Material--

The material to be used for the plastic limit test will be taken from the same carefully prepared mixture used for the liquid limit test, as described previously. Approximately 20 g of material is required for the plastic limit test.

Procedure--

The procedure will consist of the following steps:

a. Record all identifying information for the specimen on the data sheet (Plate B-5).

b. Take 2 to 5 g of the material remaining from the liquid limit test. The material will be taken at any stage of the drying process at which the mass becomes plastic enough to be shaped into a ball easily without sticking to the fingers when squeezed.

c. Shape the specimen into an ellipsoidal mass and roll it either under the root of the fingers, under the palm of the hand, or under the heel of the thumb and against the surface for rolling. Use just enough pressure to roll the sludge mass into a thread 1/8 in. in diameter as shown in Figure B-9.* When the diameter of the thread becomes 1/8 in. without crumbling, fold and knead the thread into a ball again and repeat the rolling process. Continue kneading and rolling the specimen until the sludge has dried to the point at which the rolled thread will break into numerous pieces with a diameter of 1/8 in. and lengths of about 1/8 to 3/8 in. (39), as shown in Figure B-10.

d. Place the pieces of the crumbled thread into a specimen container and determine the water content. Repeat steps b and c with another portion of the prepared material in order to check the plastic limit. The plastic limit will be reported as the average of the two tests if the two test values vary not more than 5 percent from the average; otherwise, the test will be repeated.

e. Record all weights and computations on the data sheet. All weighing should be accurate to 0.01 g, and water contents in percent computed to one decimal place.

Computations--

Computations will be made as follows.

a. After all necessary data have been recorded on the data sheet, compute the plastic limit of each specimen as follows:

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*The pressure required for rolling the thread will vary greatly depending on the toughness of the sludge.

$$\text{Plastic limit} = \frac{\text{weight of water}}{\text{weight of ovendried soil}} \times 100$$

b. Compute the plasticity index as follows.

$$\text{Plasticity index} = \text{liquid limit} - \text{plastic limit}$$

$$PI = LL - PL$$

Possible Errors--

Possible errors that would cause inaccurate determinations of the liquid and plastic limits are listed below.

General--

a. Specimen not representative. As described previously, the liquid and plastic limits must be determined using the same mixture of sludge as that used for determinations of natural water content or for other tests.

b. Specimen improperly prepared. The specimens must be thoroughly mixed and be permitted to cure for a sufficient period before testing. Erroneous results may be caused by testing airdried or ovendried sludges.

c. Inaccurate determination of water contents. The possible errors described under solids and water content determinations would greatly affect the computed liquid and plastic limits because of the small quantities of material available for the water content determinations.

d. Computational mistakes.

Liquid Limit Test--

a. Improperly constructed or adjusted liquid limit device.

b. Worn parts of liquid limit device, especially at point of contact between the cup and the base, or worn tip of grooving tool.

c. Sludge at point of contact between the cup and the base. Removal of the cup for shaping and grooving the sludge pat will also insure that the bottom of the cup and the top of the base are clean. Any sludge that has dropped onto the base can be removed with one stroke of the back of the hand just before replacing the cup.

d. Loss of moisture during test.

e. Large percentage of fibres.

Plastic Limit Test--

a. Rolling thread under fingers. The fingers will break the thread prematurely.

b. Incorrect final thread diameter. A length of 1/8-in.-diameter metal rod close at hand will help in estimating this diameter accurately.

c. Stopping the rolling process too soon. If there is any doubt as to whether the thread has crumbled sufficiently, it is better to roll the thread once more than to stop the process too soon.

Shrinkage Limit Test

Definition--

The shrinkage limit of a sludge is the water content, expressed as a percentage of the weight of the ovendried sludge, at which further loss in moisture will not cause a decrease in its volume. As part of the shrinkage limit test, the shrinkage ratio R and linear shrinkage L_s are also usually determined. The shrinkage ratio is defined as the ratio between a given volume change and the corresponding change in water content above the shrinkage limit. The linear shrinkage is defined as the decrease in one dimension of a sludge mass, expressed as a percentage of the original dimension, when the water content is reduced from a given value to the shrinkage limit.

Apparatus--

The apparatus should consist of the following:

a. Evaporating dish; a porcelain evaporating dish approximately 4-1/2 in. in diameter is recommended.

b. Shrinkage dish; a circular porcelain or monel metal dish 1-3/4 in. in diameter and 1/2 in. in height may be sufficient.

c. Glass cup, about 2 in. in diameter and about 1 in. in height with the top rim ground smooth and flat.

d. Glass plate, 3 by 3 by 1/16 in. fitted with three metal prongs for immersing the sludge pat in mercury as shown in Figure B-11.

e. Mercury, sufficient to fill the glass cup to overflowing.

f. Spatula, having a blade about 4 in. long and about 3/4 in. wide.

g. Steel straightedge.

h. Balances and oven same as those for liquid limit tests.

Preparation of Materials--

Approximately 30 g of sludge will be obtained from the thoroughly mixed portion of the material. The material to be used in the test should be prepared in the same manner as that described for the liquid limit test.

Procedure--

The procedure is as follows.

a. Record all identifying information for the specimen on a data sheet; see Plate B-6 for suggested form.

b. Place the specimen in the evaporating dish and mix it thoroughly with distilled water. The amount of water added will be sufficient to make the sludge wet enough to be readily worked into the shrinkage dish without inclusion of air bubbles. The amount of water required to give sludge the desired consistency is equal to or slightly greater than the liquid limit.

c. Coat the inside surface of the shrinkage dish with a thin layer of petroleum jelly or similar compound to prevent the sludge from adhering to the dish. Place an amount of the wetted sludge equal to about one-third the volume of the dish in the center of the dish and tap the dish on a firm surface, causing the sludge to flow to the outer edges. Continue tapping the dish until all air bubbles are eliminated from the sludge. Repeat this step for two more layers. The final layer will fill the dish completely, with some excess sludge allowed to stand above the rim of the dish. Strike off the excess sludge with a straightedge and remove all sludge adhering to the outside of the dish.

d. Weigh the full dish of sludge immediately and record the weight on the data sheet as the weight of dish and wet sludge. Allow the sludge pat to air-dry until a definite color change takes place and then oven-dry to a constant weight. Record the ovendried weight as the weight of the dish and dry sludge. Determine and record the weight of the empty dish.

e. Determine the volume of the shrinkage dish by filling the dish to overflowing with mercury,* removing the excess by pressing a glass plate firmly over the top of the dish, and weighing the amount of mercury required to completely fill the dish. The weight of the mercury divided by its density (13.53 g per cm^3) equals the volume of the inside of the shrinkage dish. Record the volume of the shrinkage dish, which is equal to the volume of the wet sludge pat.

f. Place the glass cup in the evaporating dish and fill it with mercury to overflowing. Remove the excess mercury by placing the glass plate with the three metal prongs firmly over the cup; take care not to trap air under the plate. Empty the excess mercury from the evaporating dish and remove all mercury adhering to both the glass cup and the evaporating dish with a brush.

g. Determine the volume of the sludge pat by immersing the pat in the mercury contained in the cup, using the glass plate with the three metal prongs as shown in Figure B-11. Take care not to trap air under the sludge pat or glass plate. Determine the weight of the displaced mercury and compute its volume, as indicated in step e above, and record it as the volume of the dry sludge pat.

h. Record all information pertaining to the sludge specimen such as weights, volumes, etc., on the data sheet, Plate B-6.

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*Caution should be exercised in handling mercury. Mercury may have toxic effects, particularly if spilled on the floor in areas without good ventilation. See Handling of Mercury below.

Computations--

Water Content--The water content w of the sludge at the time it was placed in the shrinkage dish is determined as follows:

$$w = \frac{W_w}{W_s} \times 100$$

where W_w = weight of water in g , obtained by subtracting the weight of the shrinkage dish plus dry sludge from the weight of the dish plus wet sludge

W_s = weight of ovendried sludge in g , obtained by subtracting the weight of the shrinkage dish from the weight of the dish plus dry sludge

Shrinkage Limit--The shrinkage limit, SL, is calculated as follows:

$$SL = w - \left(\frac{V - V_s}{W_s} \times 100\right)$$

where SL = shrinkage limit

w = water content of wet sludge pat when placed in shrinkage dish, expressed as a percentage of the weight of ovendried sludge

V = volume of wet sludge pat, cm^3

$$V_s = \frac{\text{weight of displacement mercury in evaporating dish}}{\text{specific gravity of mercury } (13.53 \text{ g per cm}^3)}$$

= volume of ovendried sludge pat, cm^3

W_s = weight of ovendried sludge pat, g

Shrinkage Ratio--The shrinkage ratio R will be determined by the following equation:

$$R = \frac{W_s}{V_s}$$

where W_s and V_s are the same as given above.

Linear Shrinkage--The linear shrinkage L_s will be determined by the following equation:

$$L_s = 100\left(1 - \sqrt[3]{\frac{100}{C + 100}}\right)$$

where C = volumetric change from a given water content w (usually LL)

$C = (w - SL)R$

Possible Errors--

Besides errors in the preparation of sludge mixtures given under Liquid and Plastic Limits, following are possible errors that would cause inaccurate determinations of shrinkage limit:

a. Inside of shrinkage dish not lubricated. If the sludge adheres to the shrinkage dish, the sludge pat may crack during drying.

b. Air bubbles included in sludge pat.

c. Sludge pat dried too rapidly. To prevent the sludge pat from cracking, it should be dried slowly, first in the humid room and then in the air of the laboratory, until a definite change in color is noted. Only then should it be placed in the oven.

d. Air bubbles trapped beneath sludge pat or glass plate when immersing pat in mercury.

Handling of Mercury (40)--

Properties--Mercury is an odorless silver-white liquid at normal temperature and pressure. Mercury has the property of forming amalgams with most metals, with the exception of platinum and iron. It is highly volatile, vaporizing at room temperature to form vapors that are highly toxic. Mercury has a specific gravity of 13.6, a boiling point of 356.9°C, and a freezing point of -38.9°C.

Health Hazards--The air concentration of mercury vapor corresponding to the equilibrium vapor pressure at room temperature (20°C) is approximately 20 mg per m^3, or 200 times the safe concentration of 0.1 mg per m^3 for continuous exposure (8 hr per day, 5 days per week); safe concentrations for shorter periods have not been proposed. Inhalation of mercury vapor of concentrations greater than 0.1 mg per m^3 over a long period of time can cause chronic poisoning. The initial symptoms of poisoning may include gingivitis, digestive disturbance, fine tremor of the extremities, irritability, excessive emotional response, and exaggerated salivation. These symptons may increase in severity and may result in permanent disability. Exposure to concentrations far greater than the maximum allowable concentration for short periods of time can cause acute illness. The exact nature, concentration, and duration of exposure determine the type and severity of symptoms. Although inhalation of mercury vapor is by far the greatest avenue of entry to the body, ingestion and absorption through the skin are also possible.

Use--Whenever possible, use of mercury for test purposes should be avoided. Personnel working in an area where mercury is used should be made aware of its hazards.

Detection--Direct reading units for determining the concentration of mercury vapor are available from the following sources:

Mine Safety Appliances Company
211 N. Braddock Ave.
Pittsburgh, Pennsylvania 15208

Union Industrial Equipment Corporation (UNICO)
150 Cove St.
Fall River, Massachusetts 02720

Acton Associates
1180 Raymond Blvd.
Newark, New Jersey 07102

Beckman Instruments, Inc.
2500 Harbor Blvd.
Fullerton, California 92634

Handling--The precautions listed below should be observed when handling mercury:

a. Mercury should not be heated without elaborate control because of the rapid increase of vapor pressure with increase in temperature.

b. Eating and smoking should not be permitted in areas where mercury is handled. Hands should be thoroughly washed after handling mercury.

c. A change of clothes should be available if clothing is contaminated.

d. Respiratory protection should be available where there is a possibility of contamination.

e. All laboratories handling mercury should have a precise plan to be followed in decontamination after a mercury spill. Some general proposals are:

  (1) Maximum general exhaust ventilation and local exhaust should be effected. Windows should be opened.

  (2) A vacuum flask or a vacuum cleaner designed for removal of mercury should be put into service immediately to recover the mercury.

  (3) The area should be decontaminated by treating with flowers of sulfur or other decontaminant.

  (4) Effectiveness of decontamination should be verified with a mercury vapor detector.

Facilities--In facilities where mercury is handled the measures listed below should be taken.

a. Floors of areas should be free of cracks and the intersection of the wall and floor should be fitted with a cove.

b. Recirculation of air in room should be discouraged because of the possibility of buildup of mercury vapor.

c. Mercury manometers should be provided with traps to insure that there will be no spillage of mercury into a process line or into room.

d. Precision equipment should be removed from areas where contamination with mercury is possible.

Transportation and Storage--When transporting and storing mercury the following precautions should be taken.

a. Mercury containers should be placed in a tray when transported within the laboratory; metal or continuous type (nonwelded) plastic containers are preferable to glass ones.

b. Mercury containers should be stored in pans that will contain any spillage.

PERMEABILITY

Permeability is a measure of the rate of flow of water or fluid through a material. The physical structure and the arrangement of constituent particles greatly affect the size and continuity of the spaces (voids or pores) between particles. These voids control the rate of flow. Such material properties and behavior as drainage, consolidation, seepage, and stability are highly dependent on the material permeability. Due to the large variation in physical structure and composition of pulp and paper-mill sludges, the permeability of sludges will show a wide variation.

The flow of water through a sludge medium is assumed to follow Darcy's law:

$$q = kiA$$

where q = rate of discharge through a sludge of cross-sectional area, A

k = coefficient of permeability

i = hydraulic gradient, the loss of hydraulic head per unit distance of flow

The coefficient of permeability, k (often termed "permeability"), is defined as the rate of discharge of water at a temperature of 20°C under conditions of laminar flow through a unit cross-sectional area of a sludge medium under a unit hydraulic gradient. The coefficient of permeability has the dimensions of a velocity and is usually expressed in centimetres per second.

Permeability computed on the basis of Darcy's law is limited to the conditions of laminar flow and complete saturation (amount of water) of the voids. In turbulent flow, the flow is no longer proportional to the first power of the hydraulic gradient. Under conditions of incomplete saturation, the flow is in a transient state and is time-dependent. Permeability decreases as the degree of consolidation increases, because of a reduction of the volume of voids.

There are several standard procedures for investigating permeability and these can be found in Reference 36. Permeability determination procedures recommended for the purposes of this manual will be presented in the section on Consolidation Tests below. An investigation of various factors affecting the permeability of sludges can be found in Reference 2.

ASH AND ORGANIC CONTENTS

Pulp and paper-mill sludge has organic material that is generally combustible and mineral materials that are incombustible and ash-forming.

A procedure (35) for determining ash content is to fire an ovendried sludge sample in a muffle furnace at a temperature of 600°C. The specimen should be fired until it has obviously been reduced to an ash (probably at least 3 hr). An alternate procedure (25) is to fire the specimen in a crucible over a bunsen burner, in which case extreme care must be taken that the ash is not carried away by the hot air currents. For either method, the ash content A_c is determined from the equation

$$A_c \text{ (percent)} = \frac{\text{weight of ash or residue}}{\text{dry weight of sludge}} \times 100$$

Percent organic content O_c can be considered (25) equal to

$$O_c = 100 - A_c$$

This is an approximate method and can be in error from 5 to 15 percent, because more than organic matter can be burned off the specimen. The ash and organic contents for a sludge can be added to the previously suggested data sheets for the same sludge.

PHYSICAL DESCRIPTION OF FIBRES

For future use, analysis, and understanding of the behavior of pulp and paper-mill sludges, some type of physical description of the fibrous content should be made. The description can be added or attached to the previously suggested data sheets. The following is a list of suggested descriptors that may be modified or added to:

a. Type of fibres.

b. Percent different average fibre lengths and diameters. Fibres could be separated by a set of different size strainers or sieves.

c. Average fibre length-to-diameter ratios (aspect ratios).

d. Average tensile strengths of fibres.

CONSOLIDATION TEST

The procedures presented in the following paragraphs are from Reference 36; however, Reference 34 is also applicable. Consolidation is the process of gradual transfer of an applied load from the pore water to the sludge structure as pore water is squeezed out of the voids. The amount of water that escapes depends on the size of the load and compressibility of the sludge. The rate at which it escapes depends on the coefficient of permeability, thickness, and compressibility of the sludge. The rate and amount of consolidation with load are usually determined in the laboratory by the one-dimensional consolidation test. In this test, a laterally confined sludge is subjected to successively increased vertical pressure, allowing free drainage from the top and bottom surfaces.

Apparatus

The apparatus should consist of the following:

a. A consolidometer with a rigid base, a consolidation ring, porous stones, a rigid loading plate, and a support for a dial indicator (Figure B-12). The various metal parts of the consolidometer will be of the same noncorrosive material. All-plastic or combination plastic and metal consolidometers may also be used to reduce electrochemical effects. The consolidometer will be of the fixed-ring type and will have a rigid base with a recess for supporting the bottom porous stone and for seating and attaching the consolidation ring. The upper surface of the recess will be grooved to permit drainage. The base will also have (1) an inundation ring to permit submergence of the specimen in water to prevent evaporation of water from the specimen during the test, and (2) suitable connections and a standpipe for making permeability tests.

b. Consolidation ring will completely and rigidly confine and support the specimen laterally. The inside diameter of the ring should not be less than 2-3/4 in. and preferably not less than 4 in.; use of larger rings for specimens of larger diameter, particularly with the fixed-ring consolidometer, will reduce the percentage of applied load carried by side friction and consequently will provide more accurate results. Normally, the ratio of the height of ring to inside diameter of ring should be between 1/4 and 1/6. The consolidation ring may be lined with a material such as Teflon to reduce the friction between the ring and the specimen. A stainless steel ring is preferable for specimens containing abrasive particles.

c. Porous stones more pervious than the specimen of sludge should be used to permit effective drainage. For routine testing, stones of high porosity should be used. The diameter of the porous stones will be such as to prevent the squeezing out of sludge through the clearance spaces between the ring and stone and to permit free compression of the specimen without binding; to minimize the possibility of binding, the sides of the upper porous stone of the fixed-ring consolidometer should be slightly tapered away from the specimen. A clearance of about 0.010 to 0.015 in. around the stone generally may be adequate; however, if very soft sludges are tested, a smaller clearance may be desirable or retainer rings may be used as shown in Figure B-12. Details of a typical retainer ring are shown in Figure B-13. The porous stones should be cleaned after every test, preferably in an ultrasonic cleaner or by boiling and flushing.

d. Loading devices of various types may be used to apply load to the specimen. The most commonly used is the beam-and-weight mechanism. The loading device should be capable of transmitting axial load to the specimen quickly and gently. Also, the equipment should be capable of maintaining the load constant for at least 24 hr. The equipment should be calibrated to insure that the loads indicated are those actually applied to the sludge specimen.

e. Dial indicator. A dial indicator reading counterclockwise, with a range of 0.50 in. and graduated to 0.0001 in., is recommended.

f. Other items needed are:

(1) Glass or plastic tubing for standpipe.

(2) Timing device, a watch or clock with second hand.

(3) Centigrade thermometer, range 0 to 50°C, accurate to 0.1°C.

(4) Deaired distilled water.

(5) Filter papers, glass plates, and a circular metal plate, approximately 0.05 in. thick and slightly less in diameter than the inside of the consolidation ring.

(6) Apparatus necessary to determine water and solid contents and specific gravity.

(7) Manometer board or suitable scales for measuring levels in standpipe.

Preparation of Specimens

Specimens will be prepared in a humid room to prevent evaporation of sludge moisture. With the consolidation ring set on a glass plate, a test specimen can be prepared by hand-placing sludge material into the ring. The sludge should be placed in uniform layers about 1/4 in. thick. Care should be taken to insure that no space in the ring is left unfilled and that the specimen is made as uniform as possible. Carefully true the surface flush with the specimen ring. Force the metal plate into the top of the specimen until it is flush with the top of the ring, thereby providing a recess for the top porous stone. Remove the metal plate.

Procedure

The procedure shall consist of the following steps:

a. Record all identifying information for the specimen, such as project number and other pertinent data, on the data sheets (Plates B-7 and P-8 are suggested forms); note any difficulties encountered in preparation of the specimen. Measure and record height and cross-sectional area of the specimen. Record weight of specimen ring and glass plate. After specimen is prepared, record the weight of the specimen plus tare (ring and glass plate). It is recommended that water content and specific gravity tests be made on representative material for every consolidation test specimen. Record the wet weight of the material used for the water content determination on the data sheet.

b. Fill the grooves in the base of the consolidometer with water. Fit the porous stone (previously saturated with water) into the base of the consolidometer. Add sufficient water so that the water level is at the top of the porous stone. Place a moist filter paper (Whatman No. 1 or equal) over the porous stone. (Be very careful to avoid entrapping any air during the assembly operations.) Place the ring with the specimen therein on top of the porous stone. Secure the ring to the base by means of clamps and screws.

c. Place a moist filter paper on top of the specimen, and then place the previously saturated top porous stone and the loading plate in position.

d. Place the consolidometer containing the specimen in the loading device.

e. Attach the dial indicator support to the consolidometer, and adjust it so that the stem of the dial indicator is centered with respect to the specimen. Adjust the dial indicator to permit the approximate maximum travel of the gage but still allow measurement of any swelling.

f. Adjust the loading device until it just makes contact with the specimen. The seating load should not exceed about 0.01 ton/ft^2 (1 ton/ft^2 $\approx$ 1 kg/cm^2).

g. Read the dial indicator, and record the reading on a data sheet (Plate B-9 is a suggested form). This is the initial reading of the dial indicator.

h. With the specimen assembled in the loading device, apply a load of 0.25 ton/ft^2 to the specimen and immediately inundate the specimen by filling the volume within the inundation ring or the chamber surrounding the specimen with water. Place a thermometer in the water, and record the temperature at 2-hr intervals. To obtain reliable time-consolidation curves the temperature should not vary more than ±2°C during the test. A load of 0.25 ton/ft^2 should be enough to prevent swelling, but if swelling occurs apply additional load increments until swelling ceases. Were the specimen permitted to swell, the resulting void ratio-pressure curve would have a more gradual curvature.

i. Continue consolidation of the specimen by applying the next load increment. The following loading schedule is considered satisfactory for routine tests: 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0 tons/ft^2, the total load being doubled by each load increment.

j. Observe and record on the data sheet (Plate B-9) the deformation as determined from dial indicator readings after various elapsed times. Readings at 0, 1/4, 1/2, 1, 2-1/4, 4, 6-1/4, 9, 12-1/4, 16, 20-1/4, 25, 36, and 49 min, and 1, 2, 4, 8, and 24 hr for each load increment are usually satisfactory. A timing device should be located near the consolidometer to insure accurately timed measurements. Allow each load increment to remain on the specimen for a minimum of 24 hr. It is desirable that the duration of all load increments be the same. During the course of the test, plot the dial reading versus time data for each load increment on a semilogarithmic plot as shown in Plate B-10. Plot the dial reading on an arithmetic scale (ordinate) and the corresponding elapsed time on a logarithmic scale (abscissa) as shown in Figure B-14. The curve shown in Figure B-14 can be converted into a time-consolidation curve using the theory of consolidation. The 100 percent consolidation or the completion of the primary consolidation is arbitrarily defined as the intersection of the tangent to the curve at the point of inflection, with the tangent to the straight-line portion representing the secondary time effect. The construction necessary for determination of the coordinates representing 100 percent consolidation and other degrees of consolidation is shown in Figure B-14. In addition to the curve above, plot the dial reading versus time-data for each load increment on a square root of time plot as shown in Plate B-11. Plot the dial reading on the arithmetic scale and the corresponding elapsed time on the square-root scale as shown in Figure B-15. The 90 percent primary consolidation is defined as the point on the data curve cut by a line coinciding at zero time with a straight line through the early portion of the data plot and having an inverse slope 1.15 times the straight line slope. After first drawing a straight line through the data, a second line is drawn having all abscissas 1.15 times as large as corresponding values on the first line. The construction necessary for determining 90 percent primary consolidation is shown in Figure B-15. Calculate the 100 percent primary compression value and time (100 percent compression = 1.1111 × 90 percent compression). Use the 100 percent compression value and time to establish the 100 percent point in Figure B-14.

k. Record on a data sheet (Plate B-12 is a suggested form) the dial reading for each load increment corresponding to a selected time (usually 24 hr) at which primary consolidation has been completed for all increments.

l. After the specimen has consolidated under the maximum load, remove the load in decrements, taking three-quarters of the load off successively for each of the first two decrements and as considered desirable thereafter. Take readings of the dial indicator as each decrement is removed to determine the rebound of the specimen. Observe, record, and plot the dial readings versus time; loads should not be removed until the dial readings are relatively constant with time or until the dial reading versus logarithm of time curve indicates completion of rebound. The final load at the end of the rebound cycle should be

0.1 ton per sq ft or less, and this load should be maintained for 24 hr in order to reduce to a tolerable amount the error in the final water content determination caused by swelling.

m. When the dial readings indicate no further significant rebound, remove the dial indicator and disassemble the apparatus. Carefully blot any excess water from the ring and surface of the specimen, eject the specimen into a dish of known weight, and weigh the dish and wet specimen; then oven-dry the wet specimen to constant weight for water content determination. Record information on Plate B-7.

n. At the end of the consolidation phase under each load increment, a falling-head permeability test should be conducted. Identifying information for the specimen is entered on the data sheet (Plate B-8 is a suggested form). A permeability test apparatus setup is also shown in Figure B-12. The net head on the specimen may be increased by use of air pressure; however, the pressure on the specimen void water should not exceed 25 to 30 percent of the vertical pressure under which the specimen has consolidated.

o. Determine (as shown in Figure B-16) and record the height of capillary rise, h_c , for the standpipe.

p. Determine and record the area of the standpipe.

q. Measure and record the initial height L , the cross-sectional area of the specimen A , and the diameter of the specimen D .

r. Determine and record the height of tailwater h_t (shown in Figure B-12).

s. Record the initial dial reading D_o (same as in step g).

t. For each load increment conduct two permeability tests. If the two tests give very different permeability values, conduct tests until the permeability value is consistent.

u. For each load increment record the load and the dial reading D_1 at the end of compression.

v. Raise the head of deaired distilled water in the standpipe above the overflow level of the consolidometer. The difference in head should not result in an excessively high hydraulic gradient during the test.

w. Begin the test by opening valve A. Start the timer. As the water flows through the specimen, measure and record the initial height of water in the standpipe h_1 , in centimeters, at initial time t_o , and the final height of water h_2 , in centimeters, at final time t_f .

x. Observe and record the temperature of the water in the consolidometer.

Computations

Consolidation Tests--

a. From the recorded data compute and record on the data sheet, Plate B-7, the initial and final water contents. Compute also the height of solids, void ratio before and after test, initial and final degree of saturation, and dry density before test using the following equations. Equations in brackets are based on units of measurements shown in Plate B-7.

$$\text{Height of solids} \quad H_s = \frac{W_s}{A \times G_s \times \gamma_w} = \left[\frac{W_s}{A \times G_s \times 1 \times 2.54} \text{ in.}\right]$$

$$\text{Void ratio before tests} \quad e_o = \frac{H - H_s}{H_s}$$

$$\text{Void ratio after test} \quad e_f = \frac{H_f - H_s}{H_s}$$

$$\text{Initial degree of saturation, percent} \quad S_o = \frac{H_{wo}}{H - H_s} \times 100$$

$$\text{Final degree of saturation, percent} \quad S_f = \frac{H_{wf}}{H_f - H_s} \times 100$$

$$\text{Dry density before test} \quad \gamma_d = \frac{W_s}{H \times A} = \left[\frac{W_s \times 62.4}{H \times A \times 2.54} \text{ lb per cu ft}\right]$$

where W_s = weight of dry sludge, g

A = area of specimen, cm^2

G_s = specific gravity of solids

γ_w = unit weight of water, g per cm^3

H = height of specimen, in.

H_f = height of specimen at end of test = $H - \Delta H$, in., where ΔH is the net change in height of specimen

$$H_{wo} = \text{original height of water} = \frac{W_{wo}}{A \times \gamma_w} = \left[\frac{W_{wo}}{A \times 1 \times 2.54} \text{ in.}\right]$$

where W_{wo} = weight of water in specimen before test, g

H_{wf} = final height of water = $\dfrac{W_{wf}}{A \times \gamma_w} = \dfrac{W_{wf}}{A \times 1 \times 2.54}$ in.

where W_{wf} = weight of water in specimen after test, g

The purpose of computing the degree of saturation at the beginning and end of the test is to obtain a check on the accuracy of the data observed and recorded. An appreciable variation from 100 percent in the computed degree of saturation at the beginning of the test for specimens that are known to be completely saturated may indicate the presence of gas or air in the specimen, or an error in the data or computations.

b. From data sheet (Plate B-9) or from dial reading-time plots (Plates B-10 and B-11), obtain the final dial reading for each load increment that corresponds to the selected time interval (usually 24 hr), and record these values on the data sheet (Plate B-12). The height of voids H_v corresponding to any given load is equal to the initial height of voids ($H - H_s$) minus the change in height (ΔH). The change in height of the specimen is equal to the accumulative change of the dial readings. Compute the void ratios of the specimen corresponding to different load increments. The void ratio is numerically equal to the height of the voids divided by the height of solids. Compute and record in Plate B-12, for each increment of pressure, the coefficient of consolidation C_v as follows:

$$C_v = \frac{0.848\left(\frac{H_I}{2}\right)^2}{t_{90}}$$

$$H_I = H - \frac{\Delta H_1 + \Delta H_2}{2}$$

where H_I = average height of the specimen for the load increment

t_{90} = time in seconds for 90 percent primary consolidation from the square root of the time plot for the load increment

ΔH_1 = change in height for the previous load increment

ΔH_2 = change in height for the load increment being considered

Compute and record in Plate B-12, for each load increment of pressure, the coefficient of secondary consolidation C_a (see Figure B-14), as follows:

$$C_a = \frac{\frac{\Delta H_s}{H}}{\text{log of one cycle}} = \frac{\frac{\Delta H_s}{H}}{1} = \frac{\Delta H_s}{H}$$

where ΔH_s = decrease in specimen height over the above log cycle

H = initial height of specimen at beginning of test for each load increment

Permeability Tests--

Compute and record in Plate B-8, for each load increment of pressure, the coefficient of permeability k_{20}, as follows:

$$k_{20} = \frac{CL}{t}\left(\log_{10}\frac{h_1 - \Delta h}{h_2 - \Delta h}\right)R_T$$

where C = constant = $(2.303 \times a)/A$

a = area of standpipe, cm^2

A = area of specimen, cm^2

L = height of specimen at end of load increment, cm

t = elapsed time of permeability test, sec

h_1 = initial height of water in standpipe, cm

h_2 = final height of water in standpipe, cm

Δh = corrected tailwater = $h_t + h_c$, cm

h_t = height of tailwater, cm

h_c = capillary rise, cm

R_T = correction factor for viscosity of water at 20°C obtained from Table B-2

Presentation of Results

The results of the consolidation tests will be shown on the report forms, Plates B-10, B-11, and B-13. The data will be shown graphically in terms of time-consolidation curves in the form shown as Plates B-10 and B-11 and in terms of void ratio-pressure and void ratio-permeability curves in the form shown as Plate B-13. To obtain the void ratio-pressure curve, the void ratio e is plotted on the arithmetic scale (ordinate) and the corresponding pressure p, in tons per square foot, on the logarithmic scale (abscissa) as shown in Figure B-17. The compression index C_c will be determined and shown on the report form (Plate B-13).

The slope of the straight-line portion of the pressure-void ratio curve on a semilogarithmic diagram is known as the compression index C_c. The compression index is defined by the equation

$$C_c = \frac{e_1 - e_2}{\log_{10} p_2 - \log_{10} p_1}$$

where p_1 and p_2 are selected pressures from the straight-line portion of the curve, and e_1 and e_2 are the corresponding void ratios. The compression index is a measure of the compressibility of a sludge. An example of the computation of C_c is shown in Figure B-17. For simplification, p_2 is often chosen to be 10 times p_1 , in which case the denominator becomes unity.

If permeability tests are performed in conjunction with the consolidation test, the coefficient of permeability for each load increment will also be plotted in the form shown as Plate B-13.

Possible Errors

Consolidation Tests--Following are possible errors that would cause inaccurate determinations of consolidation and permeability characteristics:

a. Specimen not completely filling ring. The volume of the specimen must be exactly that of the consolidation ring, otherwise there will not be complete lateral confinement.

b. Galvanic action in consolidometer. To prevent changes in the consolidation characteristics of the specimen due to galvanic currents, all metal parts of the consolidometer should be of the same noncorrosive material; it is preferable that all such parts be made of plastic.

c. Permeability of porous stones too low. The measured rate of consolidation can be markedly affected by the permeability of the porous stones. The stones should be cleaned after every test to remove embedded sludge particles.

d. Friction between specimen and consolidation ring. Soil tests have shown that over 20 percent of the load applied to a specimen can be lost by side friction in a fixed-ring consolidometer. The effect of side friction can be reduced by (1) using a larger diameter specimen, (2) using a thinner specimen, and (3) lining the consolidation ring with Teflon.

e. Inappropriate load increment factor. Depending on the purpose of the test, a load increment factor of 2.0 (that is, of doubling the total load by each load increment) may not be satisfactory.

f. Unsatisfactory height (or thickness) of specimen. The height of the specimen will determine how clearly can be detected the break in the time-consolidation curve that represents completion of primary consolidation. Depending on the character of the sludge, if the specimen is too thin, the time to 100 percent consolidation may be too rapid, while if too thick, the break in the curve may be obscured by secondary compression. Also, when a load increment factor smaller than 2.0 is used, the thickness of the specimen may have to be increased to cause enough deformation during primary consolidation to define the break in the curve.

Permeability Tests--Following are possible errors that would cause inaccurate determinations of the coefficient of permeability:

a. Stratification or nonuniform compaction of the sludge. If the specimen is compacted in layers, any accumulation of fines at the surface of the layers will reduce the measured coefficient of permeability.

b. Incomplete initial saturation of specimen.

c. Excessive hydraulic gradient. Darcy's law is applicable only to conditions of laminar flow.

d. Air dissolved in water. No other source of error is as troublesome as the accumulation of air in the specimen from the flowing water. As water enters the specimen, small quantities of air dissolved in the water will tend to collect as fine bubbles at the sludge-water interface and reduce the permeability at this interface with increasing time. The method for detecting and avoiding this problem is consistency of the permeability values.

e. Leakage along side of specimen in consolidometer.

VANE SHEAR TEST

In order to obtain a measure of the undrained sludge shear strength existing in the field for slope analysis and design, in situ vane shear tests should be conducted. The vane shear test should be run at every 2 ft of depth from the top of the sludge to the bottom. Three locations (one-third points) along each eventual slope should be investigated. The locations should be about at a distance equal to the landfill height plus 5 ft back from the bottom point at the interface between the sludge and dike. The following equipment and procedures are from Reference 41. Equipment setup for the vane shear test is shown in Figure B-18.

Torque Assembly

Requirements for the torque assembly include a gear reduction device capable of producing constant angular rotation of 1 to 6 deg/min, a calibrated proving ring with a dial gage for force measurement, a means of measuring angular rotation in degrees, and thrust bearings to support vane at ground surface. Bearings will be of the type arranged to minimize friction while preventing lateral movement of the vane. The gear reduction and proving ring device will be calibrated to measure applied torque with an error of less than 5 percent.

Procedure

The following steps describe the procedure for the vane shear test.

Advancing Borehole--

Using rotary or wash boring methods, advance borehole with or without casing to a point no closer than 18 in. above intended test elevation, maintaining as close to vertical alignment as practical. Use the following cleanout procedure and maintain hole full of drilling fluid prior to and during test.

With or Without Casing--Cleaning of borehole with or without casing should not be done through open-end drill rod or sampling spoon.

Jetting--Downward or sideward jetting is not permitted when cleaning below casing. Use any jet auger that deflects the flow of water or drilling fluid upward.

Jet Bits--Cleanout with jet bits that direct the flow downward or sideward is permitted within the casing, but should not be done within 18 in. of intended top of test elevation.

Sand Pump or Bailer--Do not use sand pump or bailer within 18 in. of intended test elevation.

Viscous Drilling Fluid--Viscous drilling fluid should be used to prevent excess swell and disturbance in the vicinity of the intended test.

Advancing Vane--

Slowly lower vane to bottom of hole and push or jack the additional 18 in., recording force necessary to advance vane.

Recording Maximum Torque T_{max}--

Immediately after vane is in position with torque assembly in place, rotate vane at constant speed of 1 deg/min and record maximum torque required.

Obtaining Remolded Strength--

To obtain remolded strength, rotate vane at rate of one revolution in 10 seconds for minimum of 12 revolutions without taking readings. Allow time delay of 5 minutes and perform the previous again.

Obtaining Friction Resistance--

Obtain friction resistance by proceeding as in steps Advancing Vane and Recording Maximum Torque, using dummy rod without vane attached. Make one determination at each elevation for vane shear tests.

Identification Samples--

After withdrawing vane from hole, remove and preserve a sample of the sludge adhering to the vane for test of water content.

Interpretation of Test Data--

Determine undrained shear strength by

$$S_{U_{vane}} = \frac{6(T_{max} - \text{friction resistance})(144)}{\pi D^2(3H + D)}$$

where T_{max} = maximum torque in inch-pound as obtained in step Recording Maximum Torque

H = vane height, in.

D = vane diameter, in.

$S_{U_{vane}}$ = undrained shear strength, psf

Friction resistance is obtained in step Obtaining Friction Resistance above.

Presentation of Data--Plot $S_{U_{vane}}$ versus depth.

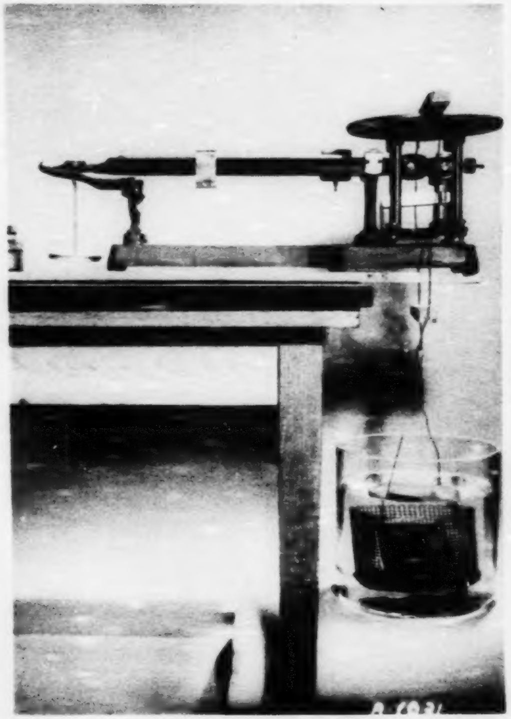


Figure B-1. Determining the weight of a sludge specimen submerged in water.

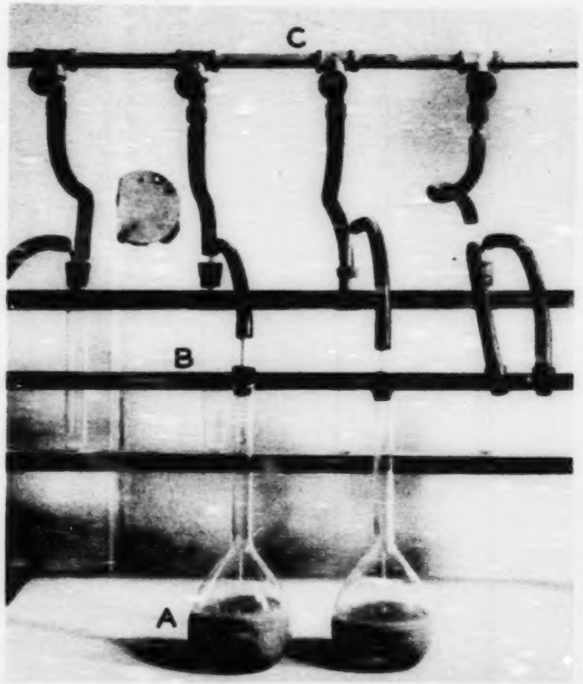


Figure B-2. Evacuating air from samples in determination of specific gravity. A, flask; B, splash trap; C, vacuum line.

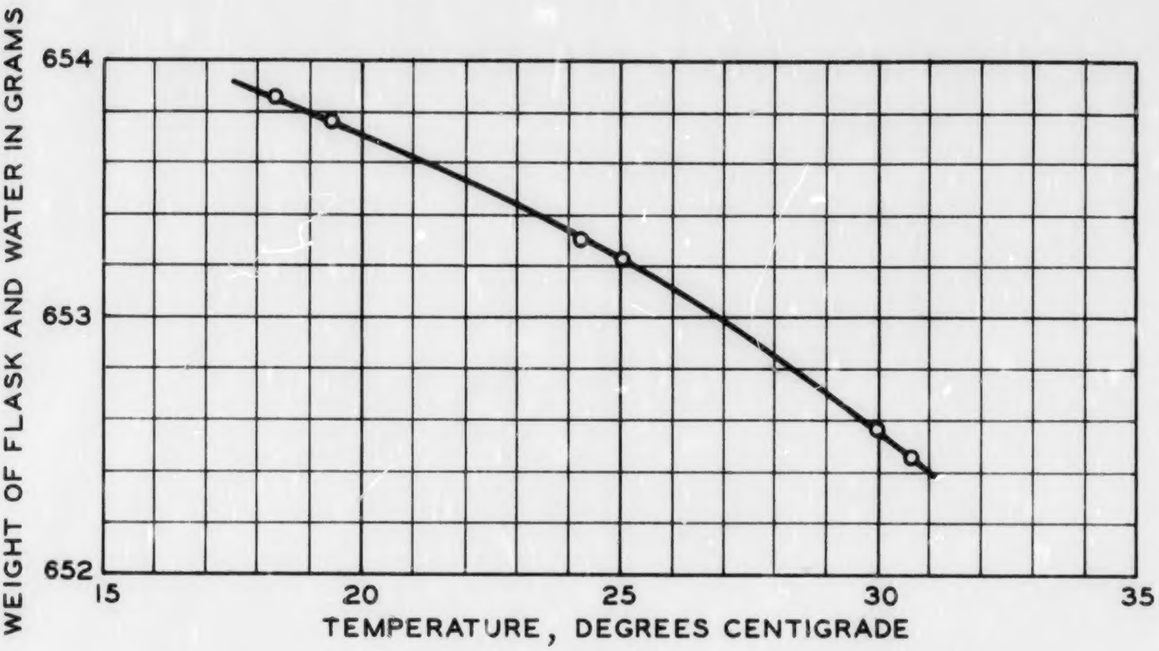


Figure B-3. Typical calibration curve of volumetric flask.

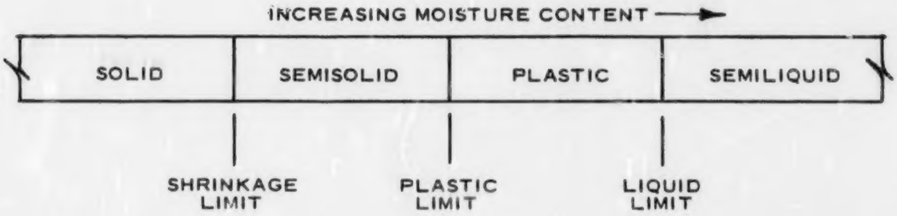
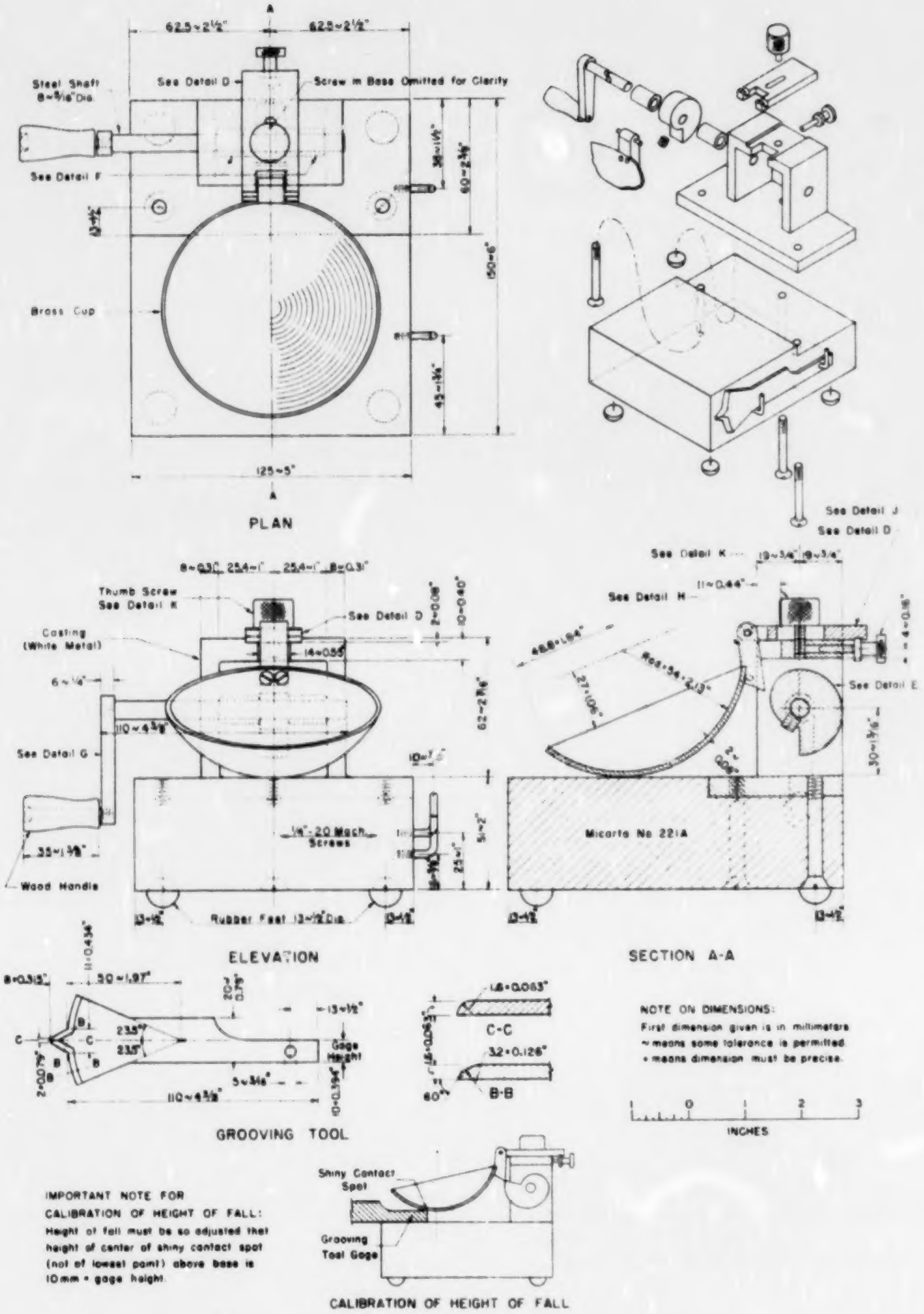

INCREASING MOISTURE CONTENT
SOLID
SEMISOLID
PLASTIC
SEMILIQUID
SHRINKAGE LIMIT
PLASTIC LIMIT
LIQUID LIMIT

Figure B-4. Stages of consistency.

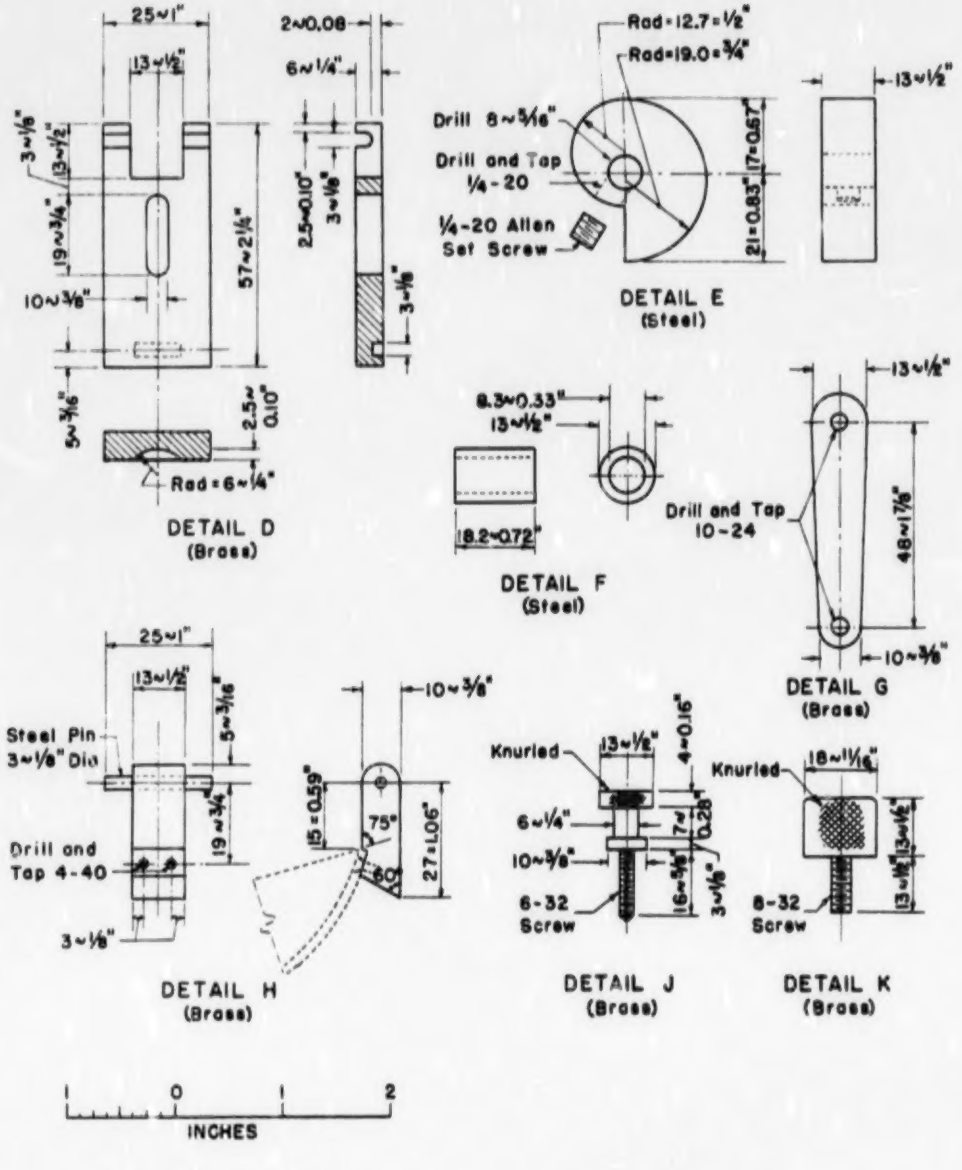


A
62.5~2½"
62.5~2½"
Steel Shaft
8~5/16" Dia
See Detail D
Screw in Base Omitted for Clarity
See Detail F
38~1½"
60~2⅜"
13~½"
150~6"
Brass Cup
45~1¾"
125~5"
PLAN
See Detail J
See Detail D
8~0.31" 25.4~1" 25.4~1" 8~0.31"
Thumb Screw
See Detail K
See Detail D
2~0.08"
10~0.40"
Casting
(White Metal)
14~0.55"
6~¼"
62~2⁷⁄₁₆"
110~4⅜"
See Detail G
10~⅜"
¼"-20 Mach. Screws
51~2"
25~1"
35~1⅜"
Wood Handle
13~½"
Rubber Feet 13~½" Dia.
13~½"
ELEVATION
See Detail K
19~3/4"
19~3/4"
11~0.44"
See Detail H
49.8~1.94"
R 68~54~2.13"
27~1.06"
4~0.16"
See Detail E
2~0.08"
30~1³⁄₁₆"
Micarta No 221A
13~½"
13~½"
SECTION A-A
8~0.315"
11~0.434"
50~1.97"
20~0.79"
13~½"
23.5°
23.5°
C
C
B
B
B
B
2~0.079"
Gage Height
5~3/16"
110~4⅜"
10~0.394"
GROOVING TOOL
1.6~0.063"
1.6~0.063"
C-C
3.2~0.126"
60°
B-B
1 0 1 2 3
INCHES
Shiny Contact Spot
Grooving Tool Gage
CALIBRATION OF HEIGHT OF FALL

NOTE ON DIMENSIONS:
First dimension given is in millimeters
~ means some tolerance is permitted.
• means dimension must be precise.

IMPORTANT NOTE FOR
CALIBRATION OF HEIGHT OF FALL:
Height of fall must be so adjusted that height of center of shiny contact spot (not of lowest point) above base is 10 mm • gage height.

Figure B-5. Liquid limit device.


25~1"
13~1/2"
2~0.08
6~1/4"
3~1/8"
13~1/2"
19~3/4"
10~3/8"
57~2 1/4"
2.5~0.10"
3~1/8"
3~1/8"
5~3/16"
2.5~0.10"
Rad=6~1/4"
DETAIL D
(Brass)
Rad=12.7=1/2"
Rad=19.0=3/4"
Drill 8~5/16"
Drill and Tap 1/4-20
1/4-20 Allen Set Screw
17=0.67"
21=0.83"
13~1/2"
DETAIL E
(Steel)
8.3~0.33"
13~1/2"
18.2~0.72"
DETAIL F
(Steel)
13~1/2"
Drill and Tap 10-24
48~1 7/8"
10~3/8"
DETAIL G
(Brass)
25~1"
13~1/2"
5~3/16"
Steel Pin 3~1/8" Dia
19~3/4"
Drill and Tap 4-40
3~1/8"
10~3/8"
15=0.59"
75°
60°
27=1.06"
DETAIL H
(Brass)
Knurled
13~1/2"
4~0.16"
6~1/4"
7=0.28"
10~3/8"
16~5/8"
3~1/8"
6-32 Screw
DETAIL J
(Brass)
Knurled
18~11/16"
13~1/2"
13~1/2"
8-32 Screw
DETAIL K
(Brass)
1
0
1
2
INCHES

NOTE ON DIMENSIONS:
First dimension given is in millimeters.
~means some tolerance is permitted.
= means dimension must be precise.

Figure B-6. Details of liquid limit device.

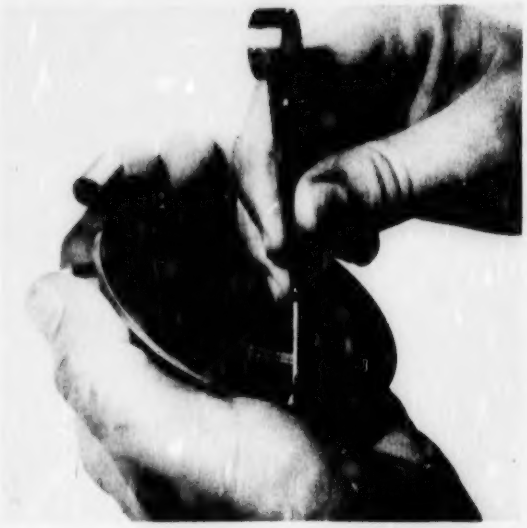


Figure B-7. Grooving liquid limit specimen.

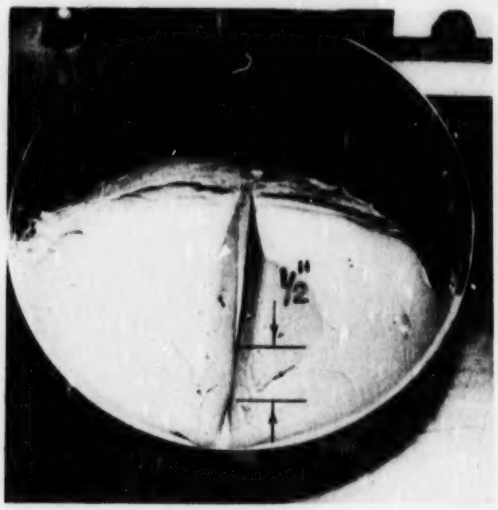


Figure B-8. Closed liquid limit groove.

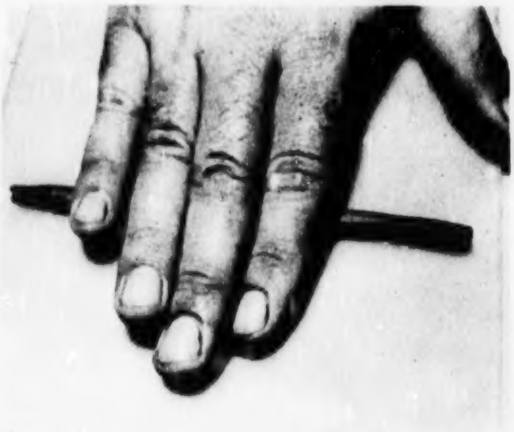


Figure B-9. Plastic limit determination.

Figure B-10. Crumbling of threads at plastic limit.

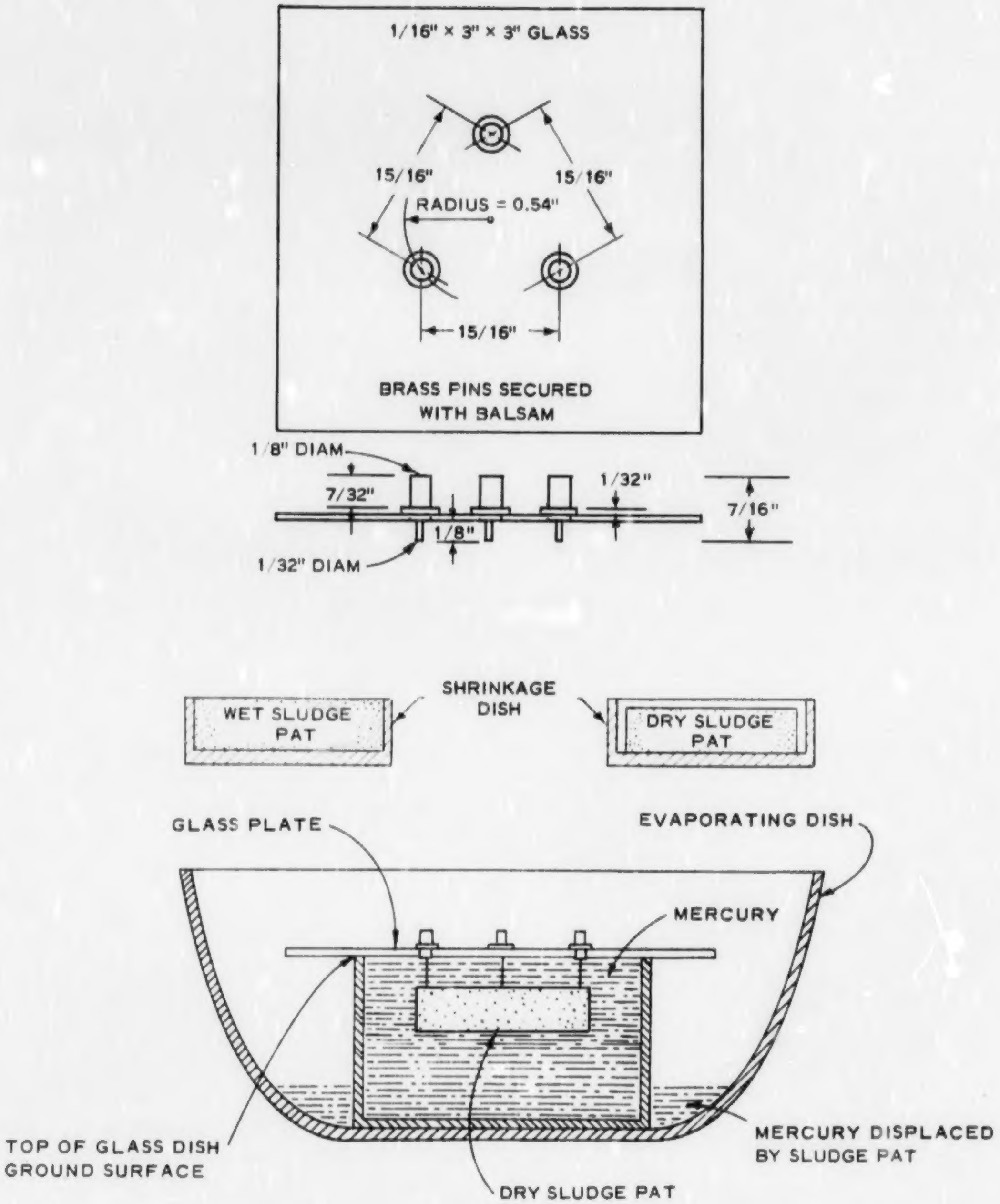
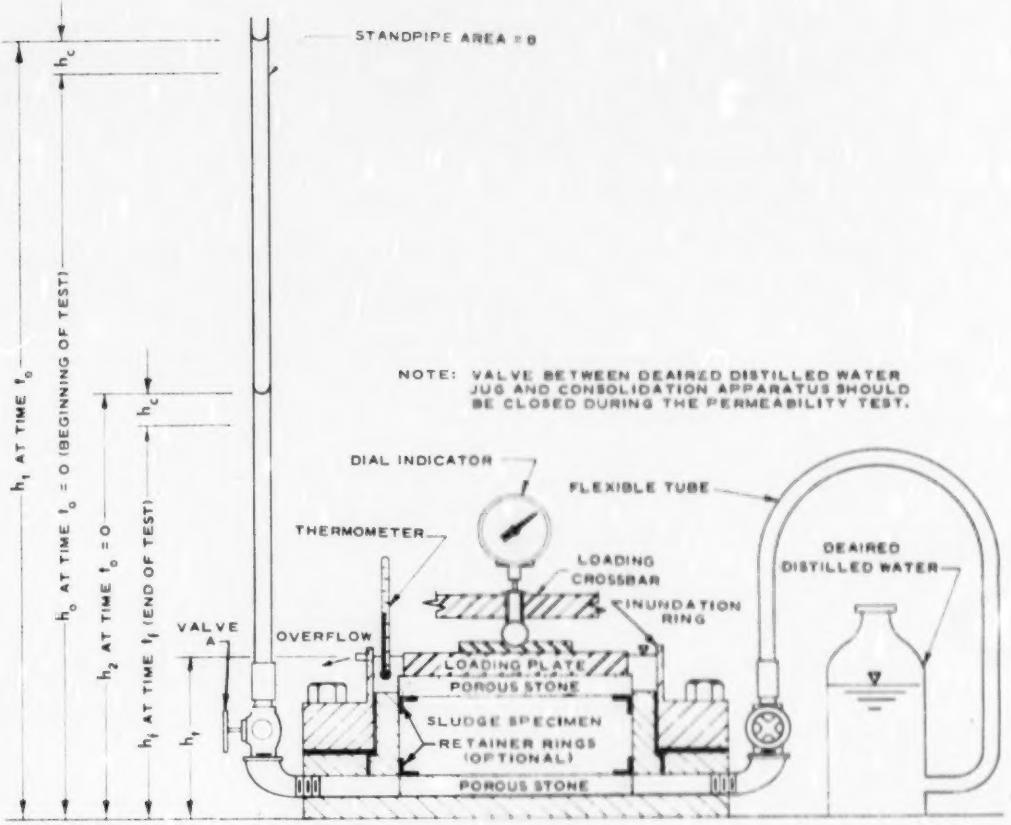

1/16" × 3" × 3" GLASS
15/16"
15/16"
RADIUS = 0.54"
15/16"
BRASS PINS SECURED WITH BALSAM
1/8" DIAM
7/32"
1/32"
7/16"
1/8"
1/32" DIAM
SHRINKAGE DISH
WET SLUDGE PAT
DRY SLUDGE PAT
GLASS PLATE
EVAPORATING DISH
MERCURY
TOP OF GLASS DISH GROUND SURFACE
MERCURY DISPLACED BY SLUDGE PAT
DRY SLUDGE PAT

Figure B-11. Apparatus for determining the volume of dry sludge pat of shrinkage limit test.


STANDPIPE AREA = a
h_c
h_1 AT TIME t_o
h_o AT TIME t_o = O (BEGINNING OF TEST)
h_2 AT TIME t_o = O
h_c
h_f AT TIME t_f (END OF TEST)
h_t
NOTE: VALVE BETWEEN DEAIRED DISTILLED WATER JUG AND CONSOLIDATION APPARATUS SHOULD BE CLOSED DURING THE PERMEABILITY TEST.
DIAL INDICATOR
FLEXIBLE TUBE
THERMOMETER
LOADING CROSSBAR
INUNDATION RING
DEAIRED DISTILLED WATER
VALVE A
OVERFLOW
LOADING PLATE
POROUS STONE
SLUDGE SPECIMEN
RETAINER RINGS (OPTIONAL)
POROUS STONE

h_a = HEIGHT OF CAPILLARY RISE

a = INSIDE AREA OF STANDPIPE

A = CROSS-SECTIONAL AREA OF SPECIMEN

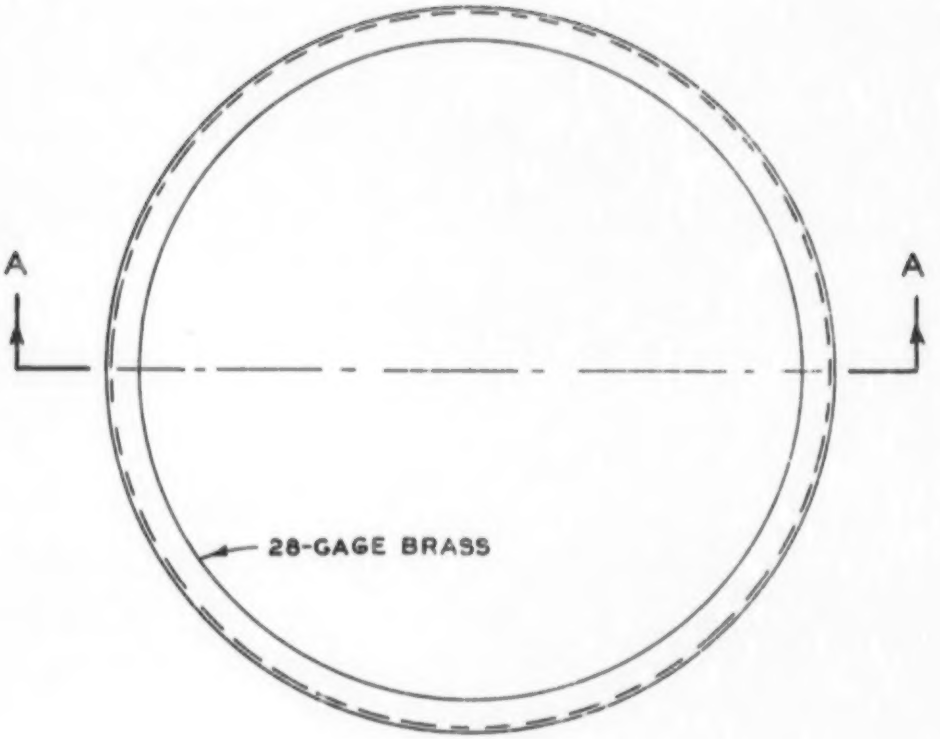
L = LENGTH OF SPECIMEN

h_o = HEIGHT OF WATER IN STANDPIPE AT TIME, t_o

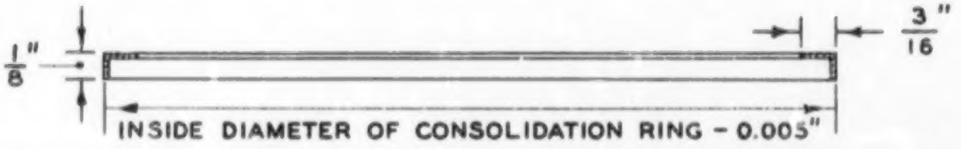
h_f = HEIGHT OF WATER IN STANDPIPE AT TIME, t_f

h_t = HEIGHT OF TAILWATER

Figure B-12. Typical consolidometer (fixed-ring type) with falling-head device for permeability test.


A
A
28-GAGE BRASS

PLAN


1"/8
3"/16
INSIDE DIAMETER OF CONSOLIDATION RING - 0.005"

SECTION A-A

Figure B-13. Typical retainer ring.

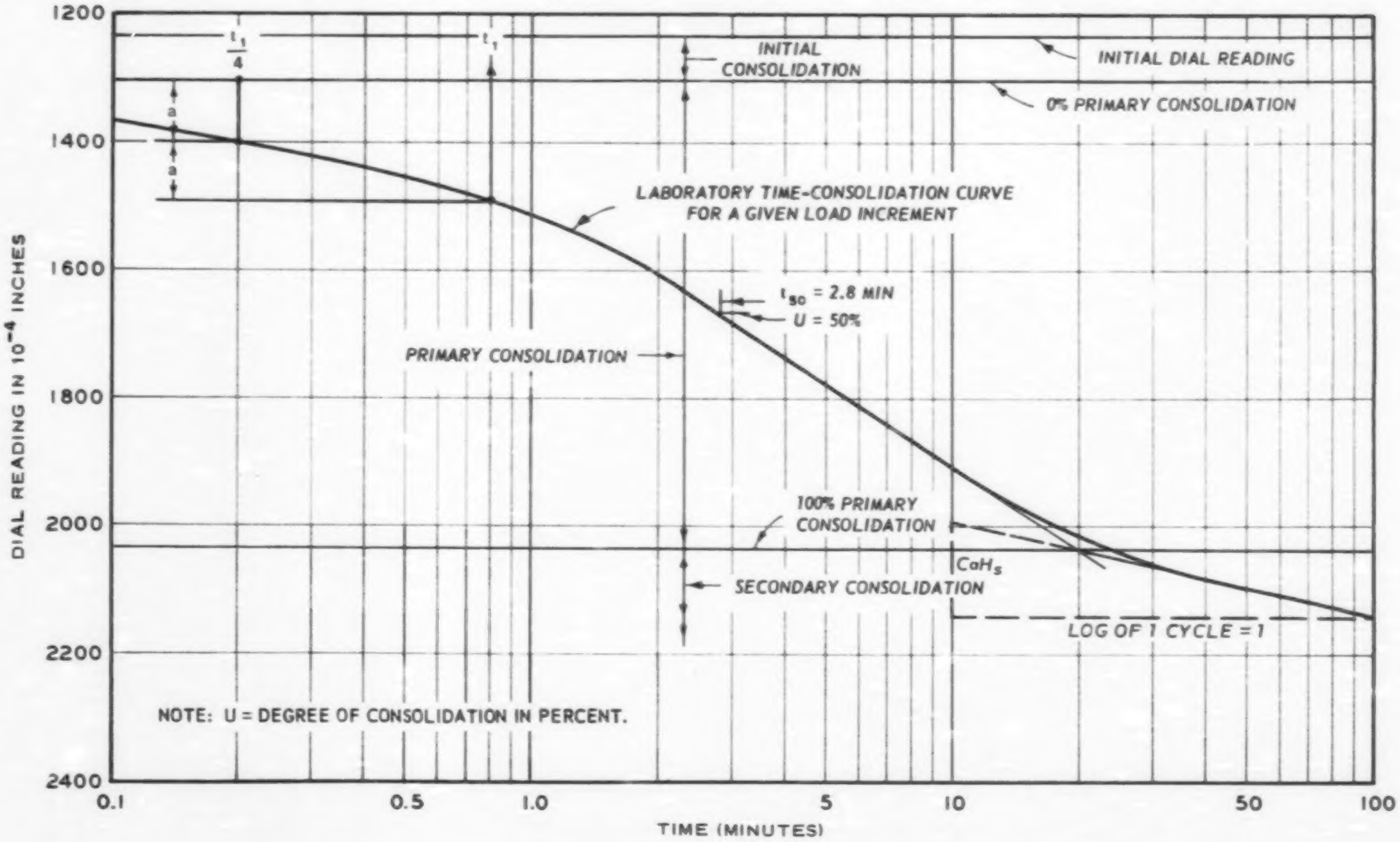


Figure B-14. Time-consolidation curve.

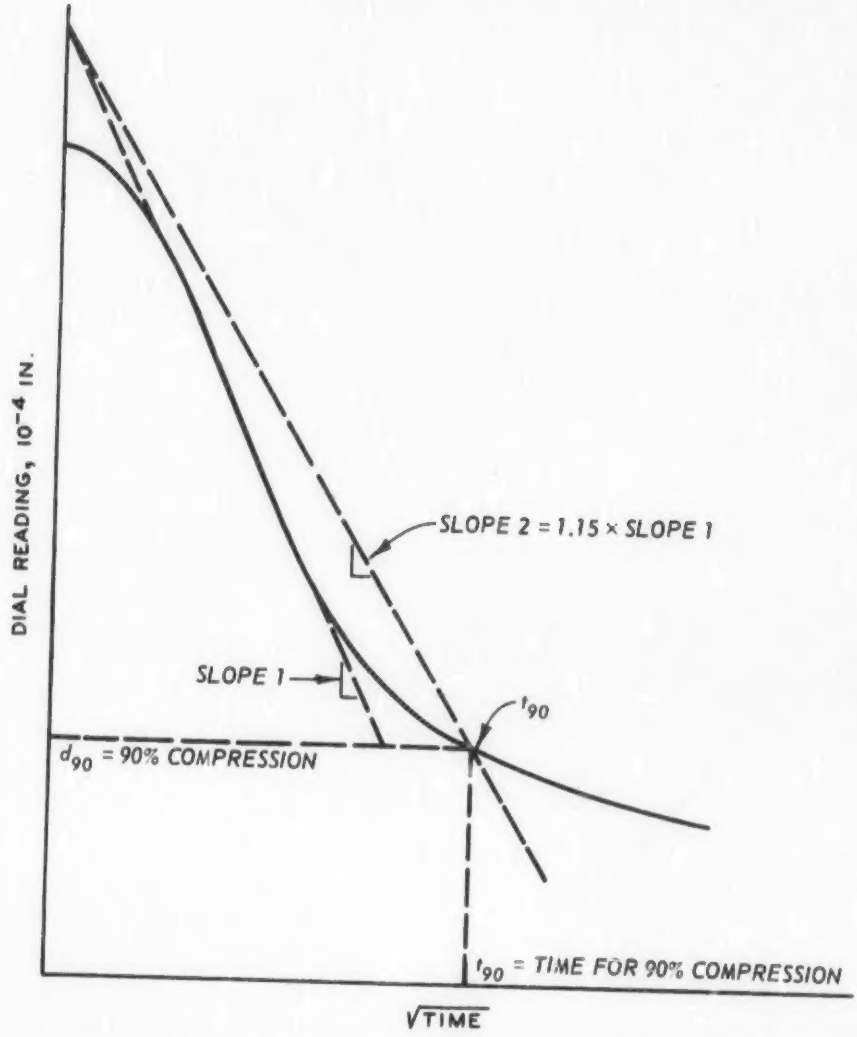


Figure B-15. Square root of time-consolidation curve.

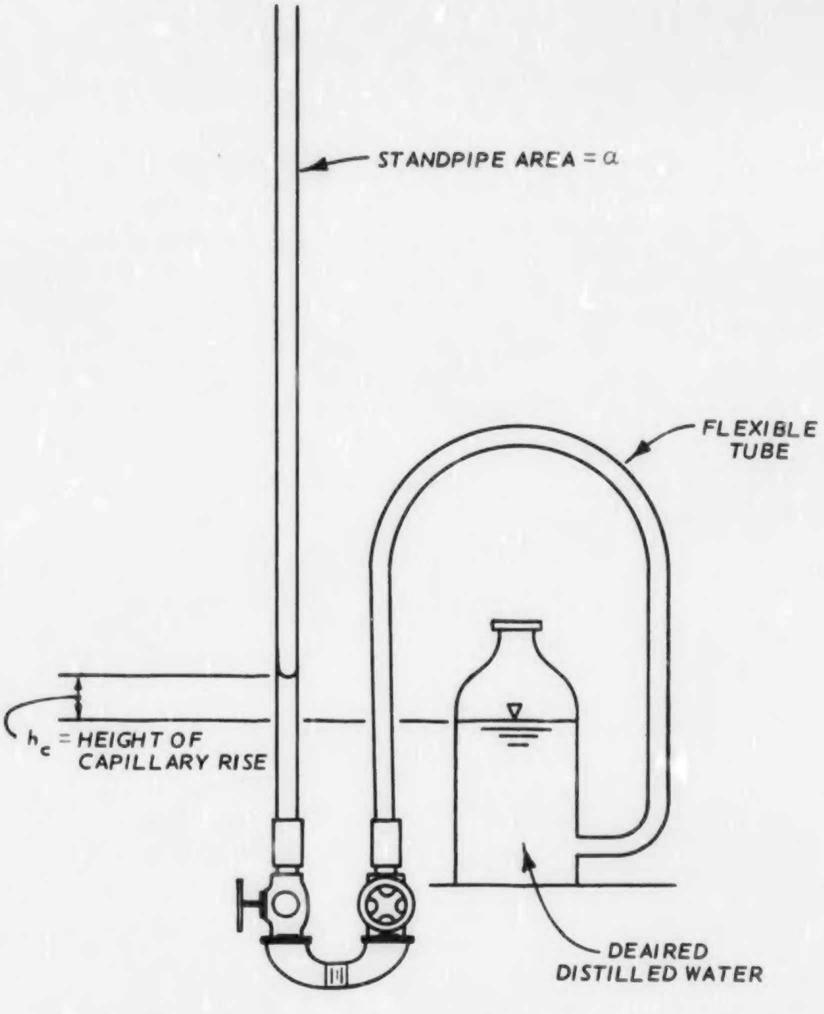

STANDPIPE AREA = a
FLEXIBLE TUBE
h_c = HEIGHT OF CAPILLARY RISE
DEAIRED DISTILLED WATER

Figure B-16. Determination of height of capillary rise.

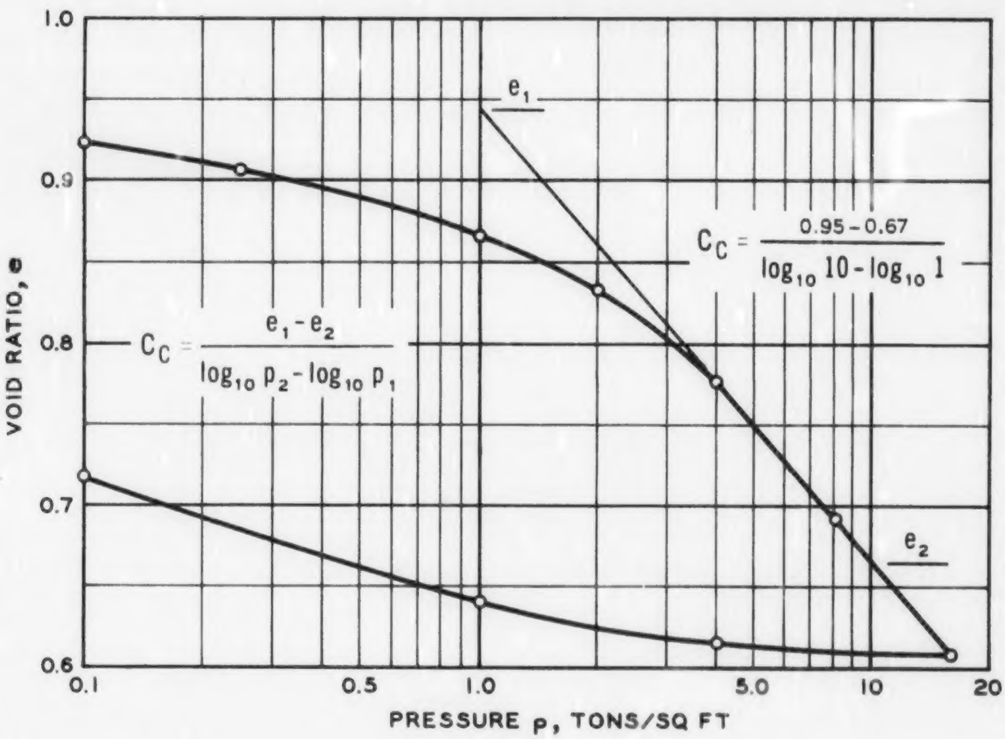


Figure B-17. Void ratio-pressure curve.

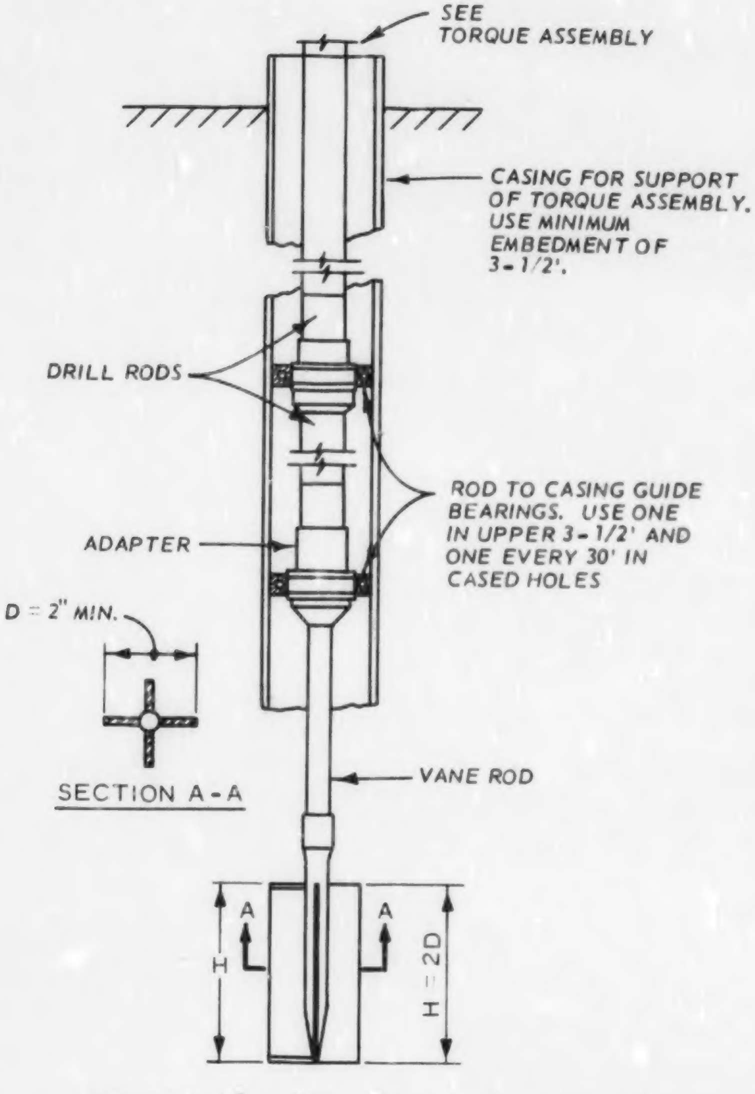

SEE
TORQUE ASSEMBLY
CASING FOR SUPPORT OF TORQUE ASSEMBLY. USE MINIMUM EMBEDMENT OF 3-1/2'.
DRILL RODS
ROD TO CASING GUIDE BEARINGS. USE ONE IN UPPER 3-1/2' AND ONE EVERY 30' IN CASED HOLES
ADAPTER
D = 2" MIN.
SECTION A-A
VANE ROD
A
A
H
H = 2D

Figure B-18. Vane snear test equipment.

TABLE B-1. RELATIVE DENSITY OF WATER AND CORRECTION FACTOR K FOR VARIOUS TEMPERATURES

Temperature °C	Relative Density*	Correction Factor, K†	Temperature °C	Relative Density	Correction Factor, K	Temperature °C	Relative Density	Correction Factor, K
18.0	0.99862	1.0004	23.0	0.99756	0.9993	28.0	0.99626	0.9980
18.1	0.99860	1.0004	23.1	0.99754	0.9993	28.1	0.99623	0.9980
18.2	0.99858	1.0004	23.2	0.99751	0.9993	28.2	0.99620	0.9980
18.3	0.99856	1.0003	23.3	0.99749	0.9993	28.3	0.99617	0.9980
18.4	0.99854	1.0003	23.4	0.99746	0.9992	28.4	0.99614	0.9979
18.5	0.99852	1.0003	23.5	0.99744	0.9992	28.5	0.99611	0.9979
18.6	0.99850	1.0003	23.6	0.99742	0.9992	28.6	0.99608	0.9979
18.7	0.99849	1.0003	23.7	0.99739	0.9992	28.7	0.99606	0.9978
18.8	0.99847	1.0002	23.8	0.99737	0.9991	28.8	0.99603	0.9978
18.9	0.99845	1.0002	23.9	0.99734	0.9991	28.9	0.99600	0.9978
19.0	0.99843	1.0002	24.0	0.99732	0.9991	29.0	0.99597	0.9977
19.1	0.99841	1.0002	24.1	0.99729	0.9991	29.1	0.99594	0.9977
19.2	0.99839	1.0002	24.2	0.99727	0.9990	29.2	0.99591	0.9977
19.3	0.99837	1.0001	24.3	0.99724	0.9990	29.3	0.99588	0.9976
19.4	0.99835	1.0001	24.4	0.99722	0.9990	29.4	0.99585	0.9976
19.5	0.99833	1.0001	24.5	0.99720	0.9990	29.5	0.99582	0.9976
19.6	0.99831	1.0001	24.6	0.99717	0.9989	29.6	0.99579	0.9976
19.7	0.99829	1.0001	24.7	0.99714	0.9989	29.7	0.99576	0.9975
19.8	0.99827	1.0000	24.8	0.99712	0.9989	29.8	0.99573	0.9975
19.9	0.99825	1.0000	24.9	0.99709	0.9989	29.9	0.99570	0.9975
20.0	0.99823	1.0000	25.0	0.99707	0.9988	30.0	0.99567	0.9974
20.1	0.99821	1.0000	25.1	0.99704	0.9988	30.1	0.99564	0.9974
20.2	0.99819	1.0000	25.2	0.99702	0.9988	30.2	0.99561	0.9974
20.3	0.99817	0.9999	25.3	0.99699	0.9988	30.3	0.99558	0.9973
20.4	0.99815	0.9999	25.4	0.99697	0.9987	30.4	0.99555	0.9973
20.5	0.99813	0.9999	25.5	0.99694	0.9987	30.5	0.99552	0.9973
20.6	0.99810	0.9999	25.6	0.99691	0.9987	30.6	0.99549	0.9973
20.7	0.99808	0.9998	25.7	0.99689	0.9987	30.7	0.99546	0.9972
20.8	0.99806	0.9998	25.8	0.99687	0.9986	30.8	0.99543	0.9972
20.9	0.99804	0.9998	25.9	0.99684	0.9986	30.9	0.99540	0.9972
21.0	0.99802	0.9998	26.0	0.99681	0.9986	31.0	0.99537	0.9971
21.1	0.99800	0.9998	26.1	0.99678	0.9986	31.1	0.99533	0.9971
21.2	0.99798	0.9998	26.2	0.99676	0.9985	31.2	0.99530	0.9971
21.3	0.99796	0.9997	26.3	0.99673	0.9985	31.3	0.99527	0.9970
21.4	0.99793	0.9997	26.4	0.99670	0.9985	31.4	0.99524	0.9970
21.5	0.99791	0.9997	26.5	0.99668	0.9984	31.5	0.99521	0.9970
21.6	0.99789	0.9997	26.6	0.99665	0.9984	31.6	0.99518	0.9969
21.7	0.99787	0.9996	26.7	0.99663	0.9984	31.7	0.99515	0.9969
21.8	0.99785	0.9996	26.8	0.99660	0.9984	31.8	0.99512	0.9969
21.9	0.99783	0.9996	26.9	0.99657	0.9983	31.9	0.99509	0.9969
22.0	0.99780	0.9996	27.0	0.99654	0.9983	32.0	0.99505	0.9968
22.1	0.99778	0.9996	27.1	0.99651	0.9983	32.1	0.99502	0.9968
22.2	0.99775	0.9995	27.2	0.99648	0.9982	32.2	0.99499	0.9968
22.3	0.99773	0.9995	27.3	0.99646	0.9982	32.3	0.99496	0.9967
22.4	0.99770	0.9995	27.4	0.99643	0.9982	32.4	0.99493	0.9967
22.5	0.99768	0.9995	27.5	0.99640	0.9982	32.5	0.99490	0.9967
22.6	0.99765	0.9994	27.6	0.99637	0.9981	32.6	0.99486	0.9966
22.7	0.99763	0.9994	27.7	0.99634	0.9981	32.7	0.99483	0.9966
22.8	0.99761	0.9994	27.8	0.99632	0.9981	32.8	0.99480	0.9966
22.9	0.99758	0.9994	27.9	0.99629	0.9981	32.9	0.99477	0.9965

*Relative density of water based on density of water at 4°C equal to unity. Data obtained from Smithsonian Tables, compiled by various authors.

†Correction factor K is found by dividing the relative density of water at the test temperature by the relative density of water at 20°C.

TABLE B-2. CORRECTION FACTOR R_T FOR VISCOSITY OF WATER AT VARIOUS TEMPERATURES

Temperature °C	Tenths of °C									
	0	1	2	3	4	5	6	7	8	9
0.0	1.783	1.777	1.771	1.765	1.759	1.753	1.747	1.741	1.735	1.729
1.0	1.723	1.717	1.711	1.705	1.699	1.694	1.688	1.682	1.676	1.670
2.0	1.664	1.659	1.654	1.648	1.643	1.638	1.632	1.627	1.622	1.616
3.0	1.611	1.606	1.601	1.596	1.590	1.585	1.580	1.575	1.570	1.565
4.0	1.560	1.555	1.550	1.545	1.540	1.535	1.531	1.526	1.521	1.516
5.0	1.511	1.507	1.502	1.498	1.493	1.488	1.484	1.479	1.475	1.470
6.0	1.465	1.461	1.457	1.452	1.448	1.443	1.439	1.435	1.430	1.426
7.0	1.421	1.417	1.413	1.409	1.404	1.400	1.396	1.392	1.388	1.383
8.0	1.379	1.375	1.371	1.367	1.363	1.359	1.355	1.351	1.347	1.343
9.0	1.339	1.336	1.332	1.328	1.324	1.320	1.317	1.313	1.309	1.305
10.0	1.301	1.298	1.294	1.290	1.287	1.283	1.279	1.276	1.272	1.269
11.0	1.265	1.262	1.258	1.255	1.251	1.248	1.244	1.241	1.237	1.234
12.0	1.230	1.227	1.223	1.220	1.217	1.213	1.210	1.207	1.203	1.200
13.0	1.197	1.194	1.190	1.187	1.184	1.181	1.178	1.175	1.171	1.168
14.0	1.165	1.162	1.159	1.156	1.153	1.150	1.147	1.144	1.141	1.138
15.0	1.135	1.132	1.129	1.126	1.123	1.120	1.117	1.114	1.111	1.108
16.0	1.106	1.103	1.100	1.097	1.094	1.091	1.089	1.086	1.083	1.080
17.0	1.077	1.075	1.072	1.069	1.067	1.064	1.061	1.059	1.056	1.053
18.0	1.051	1.048	1.045	1.043	1.040	1.038	1.035	1.033	1.030	1.027
19.0	1.025	1.022	1.020	1.017	1.015	1.012	1.010	1.007	1.005	1.002
20.0	1.000	0.998	0.995	0.993	0.990	0.988	0.986	0.983	0.981	0.979
21.0	0.976	0.974	0.972	0.969	0.967	0.965	0.962	0.960	0.958	0.955
22.0	0.953	0.951	0.949	0.947	0.944	0.942	0.940	0.938	0.936	0.933
23.0	0.931	0.929	0.927	0.925	0.923	0.920	0.918	0.916	0.914	0.912
24.0	0.910	0.908	0.906	0.904	0.901	0.899	0.897	0.895	0.893	0.891
25.0	0.889	0.887	0.885	0.883	0.881	0.879	0.877	0.875	0.873	0.871
26.0	0.869	0.867	0.866	0.864	0.862	0.860	0.858	0.856	0.854	0.852
27.0	0.850	0.848	0.847	0.845	0.843	0.841	0.839	0.837	0.836	0.834
28.0	0.832	0.830	0.828	0.826	0.825	0.823	0.821	0.819	0.818	0.816
29.0	0.814	0.812	0.810	0.809	0.807	0.805	0.804	0.802	0.800	0.798
30.0	0.797	0.795	0.793	0.792	0.790	0.788	0.787	0.785	0.783	0.782
31.0	0.780	0.778	0.777	0.775	0.774	0.772	0.770	0.769	0.767	0.766
32.0	0.764	0.763	0.761	0.759	0.758	0.756	0.755	0.753	0.752	0.750
33.0	0.749	0.747	0.746	0.744	0.743	0.741	0.739	0.738	0.736	0.735
34.0	0.733	0.732	0.731	0.729	0.728	0.726	0.725	0.723	0.722	0.720
35.0	0.719	0.718	0.716	0.715	0.713	0.712	0.711	0.709	0.708	0.706
36.0	0.705	0.704	0.702	0.701	0.699	0.698	0.697	0.695	0.694	0.693
37.0	0.691	0.690	0.689	0.687	0.686	0.685	0.683	0.682	0.681	0.679
38.0	0.678	0.677	0.675	0.674	0.673	0.672	0.670	0.669	0.668	0.666
39.0	0.665	0.664	0.663	0.661	0.660	0.659	0.658	0.656	0.655	0.654
40.0	0.653	0.652	0.650	0.649	0.648	0.647	0.646	0.644	0.643	0.642
41.0	0.641	0.639	0.638	0.637	0.636	0.635	0.634	0.632	0.631	0.630
42.0	0.629	0.628	0.627	0.626	0.624	0.623	0.622	0.621	0.620	0.619
43.0	0.618	0.616	0.615	0.614	0.613	0.612	0.611	0.610	0.609	0.608
44.0	0.607	0.606	0.604	0.603	0.602	0.601	0.600	0.599	0.598	0.597
45.0	0.596	0.595	0.594	0.593	0.592	0.591	0.590	0.588	0.587	0.586
46.0	0.585	0.584	0.583	0.582	0.581	0.580	0.579	0.578	0.577	0.576
47.0	0.575	0.574	0.573	0.572	0.571	0.570	0.569	0.568	0.567	0.566
48.0	0.565	0.564	0.564	0.563	0.562	0.561	0.560	0.559	0.588	0.557
49.0	0.556	0.555	0.554	0.553	0.552	0.551	0.550	0.549	0.548	0.548

Note: Computed from Table 170, Smithsonian Physical Tables, 8th edition.
Correction factor R_T is found by dividing the viscosity of water at the test temperature by the viscosity of water at 20°C.

WATER CONTENT – GENERAL

DATE ____________

PROJECT ____________

SAMPLE OR SPECIMEN NO.								
TARE NO.								
WEIGHT IN GRAMS	TARE PLUS WET SLUDGE							
	TARE PLUS DRY SLUDGE							
	WATER	W_w						
	TARE							
	DRY SOLIDS	W_s						
WATER CONTENT		w	%	%	%	%	%	%
SOLIDS CONTENT		S	%	%	%	%	%	%
SAMPLE OR SPECIMEN NO.								
TARE NO.								
WEIGHT IN GRAMS	TARE PLUS WET SLUDGE							
	TARE PLUS DRY SLUDGE							
	WATER	W_w						
	TARE							
	DRY SOLIDS	W_s						
WATER CONTENT		w	%	%	%	%	%	%
SOLIDS CONTENT		S	%	%	%	%	%	%
SAMPLE OR SPECIMEN NO.								
TARE NO.								
WEIGHT IN GRAMS	TARE PLUS WET SLUDGE							
	TARE PLUS DRY SLUDGE							
	WATER	W_w						
	TARE							
	DRY SOLIDS	W_s						
WATER CONTENT		w	%	%	%	%	%	%
SOLIDS CONTENT		S	%	%	%	%	%	%

$$w\% = \frac{\text{(TARE PLUS WET SLUDGE)} - \text{(TARE PLUS DRY SLUDGE)}}{\text{(TARE PLUS DRY SLUDGE)} - \text{(TARE)}} \times 100 = \frac{W_w}{W_s} \times 100, \text{ OR } w\% = 100 \times \left(\frac{100}{S} - 1\right)$$

$$S\% = \frac{W_s}{\text{(TARE PLUS WET SLUDGE)} - \text{(TARE)}} \times 100, \text{ OR } S\% = \frac{100}{\frac{w}{100} + 1}$$

REMARKS ____________

COMPUTED BY ____________ CHECKED BY ____________

PLATE B-1

UNIT WEIGHTS
(VOLUMETRIC METHOD)

DATE ____________

PROJECT ____

WATER CONTENT

SAMPLE OR SPECIMEN NO.						
TARE NO.						
WEIGHT IN GRAMS	TARE PLUS WET SLUDGE					
	TARE PLUS DRY SLUDGE					
	WATER	W_w				
	TARE					
	DRY SLUDGE	W_s				
WATER CONTENT		w	%	%	%	%
SOLIDS CONTENT		S	%	%	%	%

WEIGHT–VOLUME RELATIONS

SAMPLE OR SPECIMEN NO.						
VOLUMETRIC CONTAINER NO.						
CENTI-METERS	HEIGHT OF CONTAINER	H				
	INSIDE DIAMETER OF CONTAINER	D				
WEIGHT IN GRAMS	WET SLUDGE AND TARE					
	TARE					
	WET SLUDGE	W				
	DRY SLUDGE†	W_s				
VOLUME IN CC	WET SLUDGE (VOLUME OF CYLINDER)	V				
LB PER CU FT	WET UNIT WT = (W/V) 62.4	γ_m				
	DRY UNIT WT = (W_s/V) 62.4	γ_d				

VOLUME OF CYLINDER, V = $\frac{\pi D^2 H}{4}$ VOLUME OF WATER, $V_w = \frac{W_w}{\text{SPECIFIC GRAVITY OF WATER}^{\ddagger}}$

† IF NOT MEASURED ON ENTIRE SPECIMEN, DRY WEIGHT MAY BE COMPUTED AS FOLLOWS: $W_s = \frac{W_w}{1 + 0.01w}$

‡ SPECIFIC GRAVITY OF WATER IN METRIC SYSTEM = 1 (APPROX)

REMARKS ____

COMPUTED BY ____________________ CHECKED BY ____________________

PLATE B-2

UNIT WEIGHTS
(DISPLACEMENT METHOD)

DATE ____________

PROJECT ____

WATER CONTENT

SAMPLE OR SPECIMEN NO.						
TARE NO.						
WEIGHT IN GRAMS	TARE PLUS WET SLUDGE					
	TARE PLUS DRY SLUDGE					
	WATER	W_w				
	TARE					
	DRY SLUDGE	W_s				
WATER CONTENT		w	%	%	%	%
SOLIDS CONTENT		S	%	%	%	%

WEIGHT–VOLUME RELATIONS

SAMPLE OR SPECIMEN NO.						
TEST TEMPERATURE OF WATER, T, C						
WEIGHT IN GRAMS	SLUDGE AND WAX IN AIR					
	WET SLUDGE	W				
	WAX					
	WET SLUDGE AND WAX IN WATER					
	DRY SLUDGE†	W_s				
VOLUME IN CC	WET SLUDGE AND WAX‡					
	WAX					
	WET SLUDGE	V				
	DRY SLUDGE = W_s/G_s	V_s				
LB PER CU FT	WET UNIT WT = (W/V) 62.4	γ_m				
	DRY UNIT WT = (W_s/V) 62.4	γ_d				

VOLUME OF WAX = $\frac{\text{WEIGHT OF WAX}}{\text{SPECIFIC GRAVITY OF WAX}}$ = ____________

† IF NOT MEASURED DIRECTLY, MAY BE COMPUTED AS FOLLOWS: $W_s = \frac{W}{1+0.01w}$

‡ VOLUME OF WET SLUDGE AND WAX = $\frac{\left(\begin{array}{c}\text{WEIGHT OF WET SLUDGE}\\ \text{AND WAX IN AIR}\end{array}\right) - \left(\begin{array}{c}\text{WEIGHT OF WET SLUDGE}\\ \text{AND WAX IN WATER}\end{array}\right)}{\text{DENSITY OF WATER AT TEST TEMPERATURE}}$

REMARKS ____

COMPUTED BY ____________________ CHECKED BY ____________________

PLATE B-3

SPECIFIC GRAVITY TESTS

DATE ____________________

PROJECT ____________________

SPECIFIC GRAVITY OF SOLIDS, G_s

SAMPLE OR SPECIMEN NO.						
FLASK NO.						
TEMPERATURE OF WATER AND SLUDGE, T, °C						
DISH NO.						
WEIGHT IN GRAMS	DISH + DRY SLUDGE					
	DISH					
	DRY SLUDGE	W_s				
	FLASK + WATER AT T, °C	W_{bw}				
	$W_s + W_{bw}$					
	FLASK + WATER + IMMERSED SLUDGE	W_{bws}				
	DISPLACED WATER, $W_s + W_{bw} - W_{bws}$					
CORRECTION FACTOR		K				
$(W_s K) \div (W_s + W_{bw} - W_{bws})$		G_s				

REMARKS ____________________

____

COMPUTED BY ____________________ CHECKED BY ____________________

PLATE B-4

LIQUID AND PLASTIC LIMIT TESTS

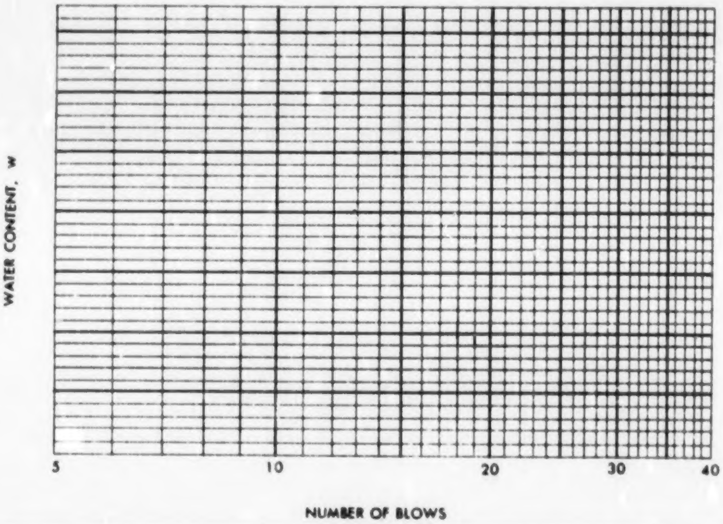
DATE ____________________

PROJECT ____

____ SAMPLE NO ____________________

LIQUID LIMIT

RUN NO.			1	2	3	4	5	6
TARE NO.								
WEIGHT IN GRAMS	TARE PLUS WET SLUDGE							
	TARE PLUS DRY SLUDGE							
	WATER	W_w						
	TARE							
	DRY SLUDGE	W_s						
WATER CONTENT		w						
NUMBER OF BLOWS								



LL ____________________

PL ____________________

PI ____________________

PLASTIC LIMIT

RUN NO			1	2	3	4	5	NATURAL WATER CONTENT
TARE NO.								
WEIGHT IN GRAMS	TARE PLUS WET SLUDGE							
	TARE PLUS DRY SLUDGE							
	WATER	W_w						
	TARE							
	DRY SLUDGE	W_s						
WATER CONTENT		w						
PLASTIC LIMIT								

REMARKS ____

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____________________________ COMPUTED BY ____________________ CHECKED BY ____________________

PLATE B-5

SHRINKAGE LIMIT TEST

DATE ____________________

PROJECT ____

SAMPLE OR SPECIMEN NO.						
SHRINKAGE DISH NO.						
WEIGHT IN GRAMS	DISH PLUS WET SLUDGE					
	DISH PLUS DRY SLUDGE					
	WATER	W_w				
	SHRINKAGE DISH					
	DRY SLUDGE	W_s				
	DISPLACED MERCURY + EVAPORATING DISH					
	EVAPORATING DISH					
	DISPLACED MERCURY					
VOLUME IN CC	SHRINKAGE DISH (WET SLUDGE PAT)	V				
	VOLUME OF DRY SLUDGE	V_s				
	$V - V_s$					
	$\frac{V - V_s}{W_s} \times 100$					
WATER CONTENT $= \frac{W_w}{W_s} \times 100$		w	%	%	%	%
SHRINKAGE LIMIT		SL				
SHRINKAGE RATIO		R				

$$V_s = \frac{\text{WEIGHT OF DISPLACED MERCURY}}{\text{SPECIFIC GRAVITY OF MERCURY (13.53 g/cc)}}$$

$$SL = \text{WATER CONTENT OF WET SLUDGE PAT} - \left(\frac{\text{VOLUME OF WET SLUDGE PAT} - \text{VOLUME OF OVEN-DRY SLUDGE PAT}}{\text{WEIGHT OF OVEN-DRY SLUDGE PAT}}\right) = w - \left(\frac{V - V_s}{W_s} \times 100\right)$$

$$R = \frac{\text{WEIGHT OF OVEN-DRY SLUDGE PAT}}{\text{VOLUME OF OVEN-DRY SLUDGE PAT}} = \frac{W_s}{V_s}$$

REMARKS ____

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COMPUTED BY ____________________ CHECKED BY ____________________

PLATE B-6

CONSOLIDATION TEST

(Specimen Data)

Date ______________

Project ____

______________________________ Sample No. ______________

Classification							
			Before Test			After Test	
			Specimen		Extra material	Specimen	
Tare No.			Ring and plates				
Weight in grams	Tare plus wet sludge						
	Tare plus dry sludge						
	Water	W_w	W_{wo}			W_{wf}	
	Tare						
	Dry soil	W_s	W_{so}			W_{sf}	
	Water content	w	w_o	%	%	w_f	%

Consolidometer No.		Area of specimen, A, sq cm	
Weight of ring, g		Height of specimen, H, in.	
Weight of plates, g		Sp gr of solids, G_s	

Height of solids, $H_s = \frac{W_{so}}{A \times G_s \times \gamma_w} = \frac{\qquad}{\quad \times \qquad \times 1 \times 2.54} =$ in.

Original height of water, $H_{wo} = \frac{W_{wo}}{A \times \gamma_w} = \frac{\qquad}{\qquad \times 1 \times 2.54} =$ in.

Final height of water, $H_{wf} = \frac{W_{wf}}{A \times \gamma_w} = \frac{\qquad}{\qquad \times 1 \times 2.54} =$ in.

Net change in height of specimen at end of test, $\Delta H =$ in.

Height of specimen at end of test, $H_f = H - \Delta H =$ in.

Void ratio before test, $e_o = \frac{H - H_s}{H_s} = \underline{\qquad\qquad} =$

Void ratio after test, $e_f = \frac{H_f - H_s}{H_s} = \underline{\qquad\qquad} =$

Degree of saturation before test, $S_o = \frac{H_{wo}}{H - H_s} = \underline{\qquad\qquad} =$ %

Degree of saturation after test, $S_f = \frac{H_{wf}}{H_f - H_s} = \underline{\qquad\qquad} =$ %

Dry density before test, $\gamma_d = \frac{W_s}{H \times A} = \frac{\qquad \times 62.4}{\quad \times \qquad \times 2.54} =$ lb/cu ft

Remarks ____

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______________________ Computed by ______________ Checked by ______________

PLATE B-7

FALLING-HEAD PERMEABILITY TEST
WITH CONSOLIDOMETER

DATE ____________________

PROJECT ____

SAMPLE OR SPECIMEN NO.

WT IN GRAMS	TARE PLUS DRY SLUDGE			DIAMETER OF SPECIMEN, CM	D	
	TARE			AREA OF SPECIMEN, SQ CM	A	
	DRY SOLIDS	W_s		INITIAL HEIGHT OF SPECIMEN, CM	L	
SPECIFIC GRAVITY		G_s		INITIAL VOL OF SPEC, CC = AL	V	
VOL OF SOLIDS, CC = $W_s \div G_s$		V_s		INITIAL VOID RATIO = $(V - V_s) \div V_s$	e	
AREA OF STANDPIPE, SQ CM		a		CONSTANT = $(2.303 \times a) \div A$	C	
CAPILLARY RISE, CM		h_c		INITIAL DIAL READING, IN.	D_o	
HEIGHT OF TAILWATER, CM		h_t		CORRECTED TAILWATER, CM, $h_t + h_c$	Δh	

TEST NO.		1		2		3	
LOAD INCREMENT, T/SQ FT	P						
DIAL READING AT START, IN.	D_1						
CHANGE IN HT OF SPEC, IN. = $D_o - D_1$	ΔD						
HT OF SPEC, CM = $L - 2.54\,\Delta D$	L						
VOID RATIO = $(AL - V_s) \div V_s$	e						
		1a	1b	2a	2b	3a	3b
INITIAL TIME	t_o						
FINAL TIME	t_1						
ELAPSED TIME, SEC = $t_1 - t_o$	t						
INITIAL HEIGHT, CM	h_1						
FINAL HEIGHT, CM	h_2						
WATER TEMPERATURE, °C	T						
VISCOSITY CORRECTION FACTOR(1)	R_T						
COEFFICIENT OF PERMEABILITY,(2) CM/SEC	k_{20}						
	AVG						

(1) CORRECTION FACTOR FOR VISCOSITY OF WATER AT 20 C OBTAINED FROM TABLE 3.

(2) $$k_{20} = 2.303\,\frac{a}{A}\,\frac{L}{t}\left(\text{LOG}\,\frac{h_1 - \Delta h}{h_2 - \Delta h}\right)R_T = \frac{CL}{t}\left(\text{LOG}\,\frac{h_1 - \Delta h}{h_2 - \Delta h}\right)R_T$$

REMARKS ____

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____________________ COMPUTED BY ____________________ CHECKED BY ____________________

PLATE B-8

CONSOLIDATION TEST
(TIME-CONSOLIDATION DATA)

DATE ____________

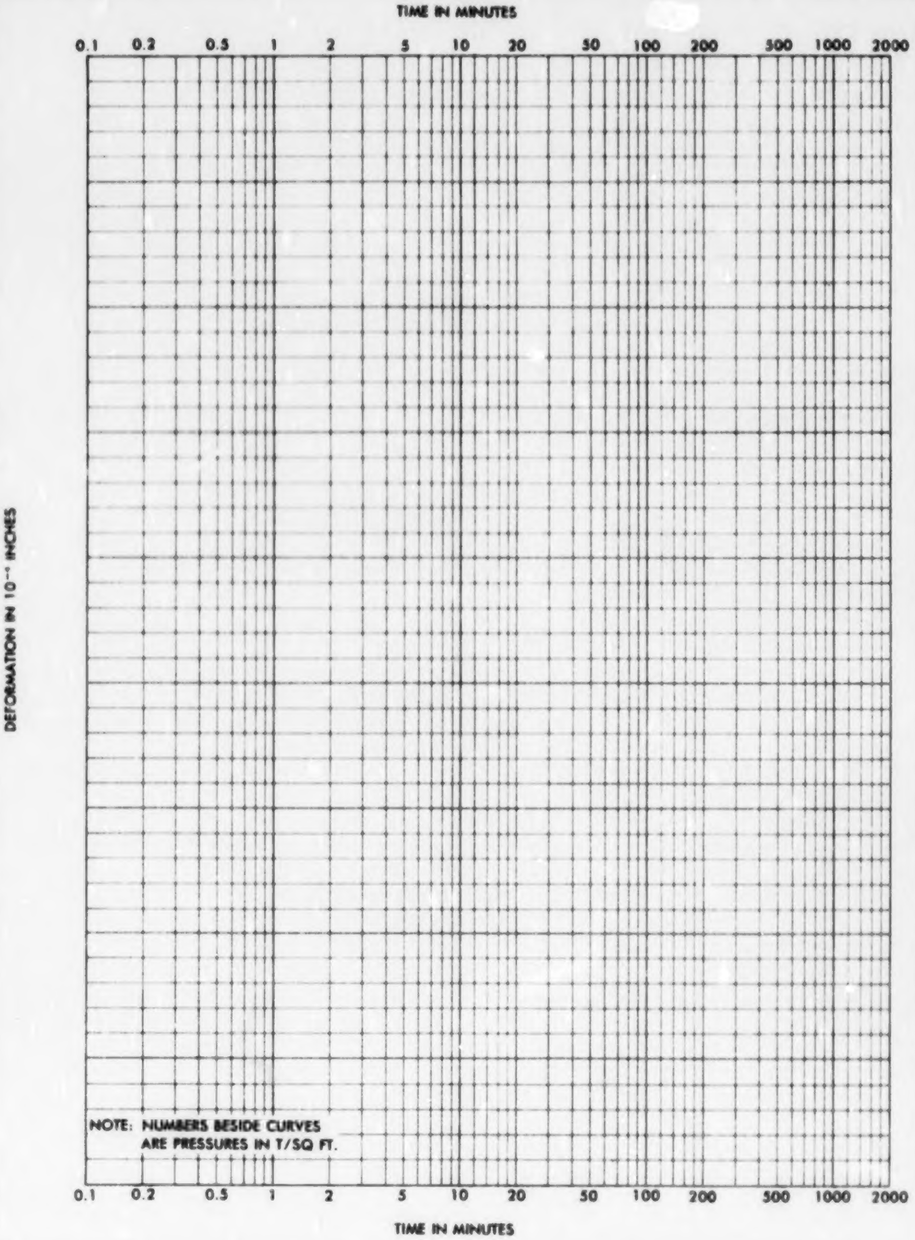
PROJECT ____

SAMPLE NO. ____________ CONSOL. NO. ____________

DATE AND PRESSURE	TIME	ELAPSED TIME, MIN	DIAL RDG. 10^{-4} IN.	TEMP °C	DATE AND PRESSURE	TIME	ELAPSED TIME, MIN	DIAL RDG. 10^{-4} IN.	TEMP °C

CONDUCTED BY ____________

PLATE B-9



PROJECT

AREA

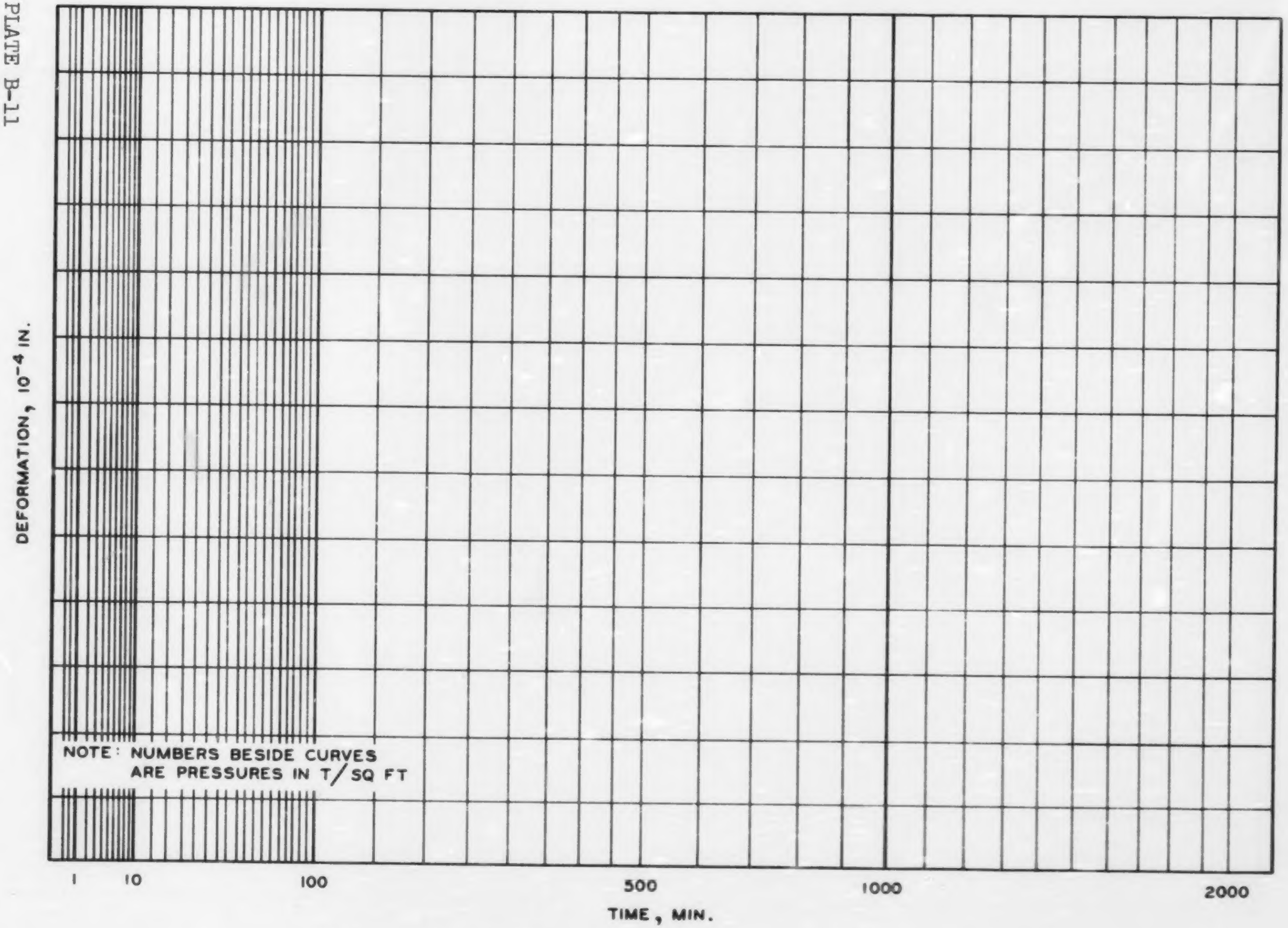
SAMPLE NO.

DATE

CONSOLIDATION TEST—TIME CURVES

PLATE B-10

PLATE B-11



Dial reading versus time-data for each load increment

CONSOLIDATION TEST
(COMPUTATION OF VOID RATIOS)

DATE ____________

PROJECT ____________

SAMPLE NO. ____________ CONSOLIDOMETER NO. ____________

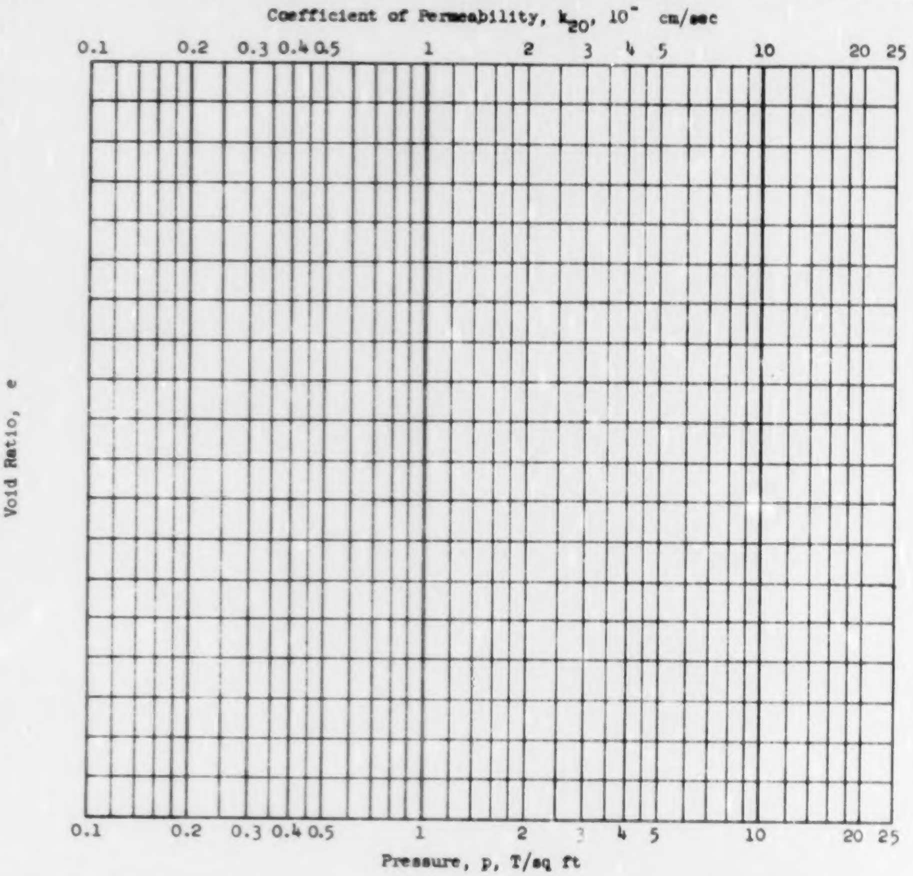
PRESSURE, p T/SQ FT	DATE INCREMENT APPLIED	TIME IN MIN INCREMENT EFFECTIVE	DIAL READING 10^{-4} IN.	CHANGE IN HEIGHT, ΔH 10^{-4} IN.	HEIGHT OF VOIDS, H_v 10^{-4} IN.	VOID RATIO, e	COEFFICIENT OF CONSOLIDATION C_v, 10^{-4} IN.^{2}/SEC	COEFFICIENT OF SECONDARY COMPRESSION C_α, 10^{-3}/MIN

HEIGHT OF VOIDS, $H_v = (H - H_s) - \Delta H =$ ____________

VOID RATIO, $e = \frac{H_v}{H_s}$

CONDUCTED BY ____________ COMPUTED BY ____________ CHECKED BY ____________

PLATE B-12



Type of Specimen		Before Test		After Test	
Diam in.	Ht in.	Water Content, w_o	%	w_f	%
Compression Index, C_c		Void Ratio, e_o		e_f	
Classification		Saturation, S_o	%	S_f	%
LL	G_s	Dry Density, γ_d	lb/ft^3		
PL		k_{20} at e_o = × 10^{-} cm/sec			

Remarks	Project
	Area
	Sample No.
	Date
	CONSOLIDATION TEST REPORT

PLATE B-13